MANUFACTURING TECHNOLOGIES I

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1.1 Manufacturing processes

The manufacturing process includes all transformations the raw material undergoes until it becomes the finished product.

The technological process is a part of the manufacturing process, which involves:

•Modifying the shape, dimensions, surface roughness, and material properties.

To achieve the finished part according to the execution drawing, the following steps are involved:

•Technological process for obtaining the blank

•Mechanical processing technology

•Technological process of heat treatments

•Technological assembly process

1.1.1 Technological process for obtaining the workpiece

This process is a part of the overall technological process, aiming to achieve the following for the semi-finished product:

•Desired material quality (such as steel, cast iron, brass, bronze)

•Specific physical and mechanical properties

•A geometric shape that closely approximates the finished part

1.1.2 Mechanical processing technology

Mechanical processing technology is the part of the manufacturing process focused on altering the geometric shape and dimensions of the part.

1.1.3 Technological process of heat treatment

The heat treatment process is a stage in manufacturing focused on modifying the material's structure to enhance its physical and mechanical properties.

1.1.4 Technological assembly process

The assembly process involves combining individual parts into the final product, ensuring that the finished assembly meets the technical specifications and requirements.

1.2 Technological process components

•**Operation:** An operation is a continuous task conducted at a single job site, using the same machine unit (MU) on one or more blanks. It may require the blank to be clamped multiple times and is divided into several phases.

•**Phase:** A single blank installation goes through a process in which one or more surfaces are machined simultaneously using one or more tools mounted in the same tool holder and operating in a single cutting mode.

Each phase can involve one or multiple passes, depending on the thickness of the material layer to be removed. Each pass removes a specified layer of material from the blank.

•**Passing:** This is a part of the phase that involves removing a single layer of material from the blank in one piece.

•**Movement:** Movement refers to the action of either the working or auxiliary unit, moving in a specified direction, at a set speed, and by a certain amount. During this movement, the main shaft remains in a constant state of motion. This is a fundamental element of the machining program and is often called a sequence.

•**Seating** refers to the positioning and securing of the workpiece relative to the machine and specific datum surfaces (SDVs) necessary for machining. This ensures the workpiece is correctly aligned and held firmly in place, which is essential for achieving accurate and consistent machining results. Proper seating minimizes errors caused by misalignment and helps maintain the intended geometric relationships during the machining process.

1.3. Production clasification:

1.3.1. Individual production

This type of production is used in specialized industries and involves the manufacturing of one-off or low-quantity items, each typically customized to specific requirements.

It is characterized by non-repeatable manufacturing, where there is no planned repeatability; each product may be unique or produced in small quantities.

The production process relies on:

Universal machine units: Versatile machines grouped by type and size to handle a variety of tasks based on capability.

Universal standard devices and tools: General-purpose tools used to maximize flexibility in the production process.

Highly skilled workforce: A skilled labor force is essential to operate versatile equipment and manage diverse tasks.

Other key features include:

Irregular machine loading: Machines experience variable workloads due to the non-continuous nature of production.

Minimal technological documentation: Only essential documentation, such as basic technology sheets, is prepared to streamline operations.

Norming work based on statistical similarity: Standards and benchmarks are established using statistical analysis of similar operations. This allows flexibility by relying on historical data and comparable parts or processes, rather than fixed norms.

Main feature: Production elasticity, enabling adaptability to varying product requirements and smaller production volumes.

1.3.2 Series Production

In this type, products are manufactured in batches or small series. Each batch consists of a set number of items with similar characteristics. This approach enables moderate customization while maintaining a balance between efficiency and consistency. Series production follows a cyclical process in which many identical products are created through repeated operations.

Features of series production:

- Use of universal and partially specialized machine tools
- Application of fitting adjustment methods instead of full interchangeability
- Arrangement of machine tools according to the technological flow of part groups
- Detailed technological documentation
- Combined normalization: both analytical and time-based methods are used

1.3.3 Mass production

This type involves the continuous production of standardized products on a large scale, typically over an extended period (1 to 3 years). Mass production maximizes efficiency and minimizes costs through high levels of automation and consistency, making it ideal for high-demand, uniform products.

Features of mass production:

- Successive execution of the same operation at most workstations
- Jobs arranged in the sequence of the technological process

- Use of specialized machinery (e.g., aggregates and dedicated lines)
- Specialized, automated, and fully interchangeable production systems
- Low-skilled workforce
- Detailed documentation of the technological process

Chapter 2. Mechanics of chip formation in metal cutting

2.1 Types of chips

Chips can be either a few millimeters to a few centimeters long or a few millimeters short.

These lengths indicate different things [6]:

Type	①	②	③	④	⑤
Appearance					
Length	May range from tens of centimetres to several meters		From few millimeters to few centimeters		
Number of Loops	Irregular	Over 5 loops	1~ 5 loops	1 loop	Less than 1 loop

Types 1 and 2, with long chips, can wrap around the workpiece or machine, posing a risk of scratches or stopping operations. Chip length is a function of cutting conditions, but ductile materials such as aluminum, stainless steel, and copper alloys are naturally capable of producing long chips. This issue can be addressed by using tools equipped with a chip breaker function, which intermittently cuts the chips, or by introducing machines equipped with an oscillation cutting system that creates minute vibrations to prevent the formation of long chips.

Types 3 and 4 are commonly selected because they indicate stable cutting conditions. Their short length reduces the risk of wrapping and facilitates evacuation, which improves efficiency.

Type 5 indicates cutting conditions that are unstable, possibly due to insufficient parameters or tools. The chips are dispersed, and there is a tendency to have rough surface finish.

1. Discontinuous chips

Discontinuous chips are produced during the processing of brittle materials. This type of chip formation occurs when using cutting tools with small clearance angles, high feed rates, and low cutting speeds.

2. Continuous chips

Continuous chips are generated when machining ductile materials. This process involves the use of cutting tools with large clearance angles, small feed rates, and high cutting speeds, often coupled with the application of various coolants to facilitate the cutting process.

3. Continuous chips with irregularities

Continuous chips with irregularities occur when there is high friction between the tool and the material, leading to elevated temperatures in the machining area.

2.2 Variables of the cutting technology process

1. Dependent variables

Dependent variables are those that are influenced by the cutting process. Key dependent variables include:

- **Shape of the resulting chips**: The geometric characteristics of the chips produced during machining.

- **Magnitude of moments and forces**: The forces and moments experienced during the cutting process, which can affect tool performance and chip formation.

- **Energy consumption and heat generation**: The energy consumed in the machining process, as well as the heat generated in the workpiece, chip, and tool.

- **Quality of the machined surface**: The surface finish and integrity of the workpiece after machining.

2. Independent variables

Independent variables are the factors that can be controlled or adjusted in the cutting process. These may include:

- Cutting speed
- Feed rate
- Tool geometry (clearance angle, rake angle, etc.)
- Type of material being machined
- Coolant application

2.3 Orthogonal cutting

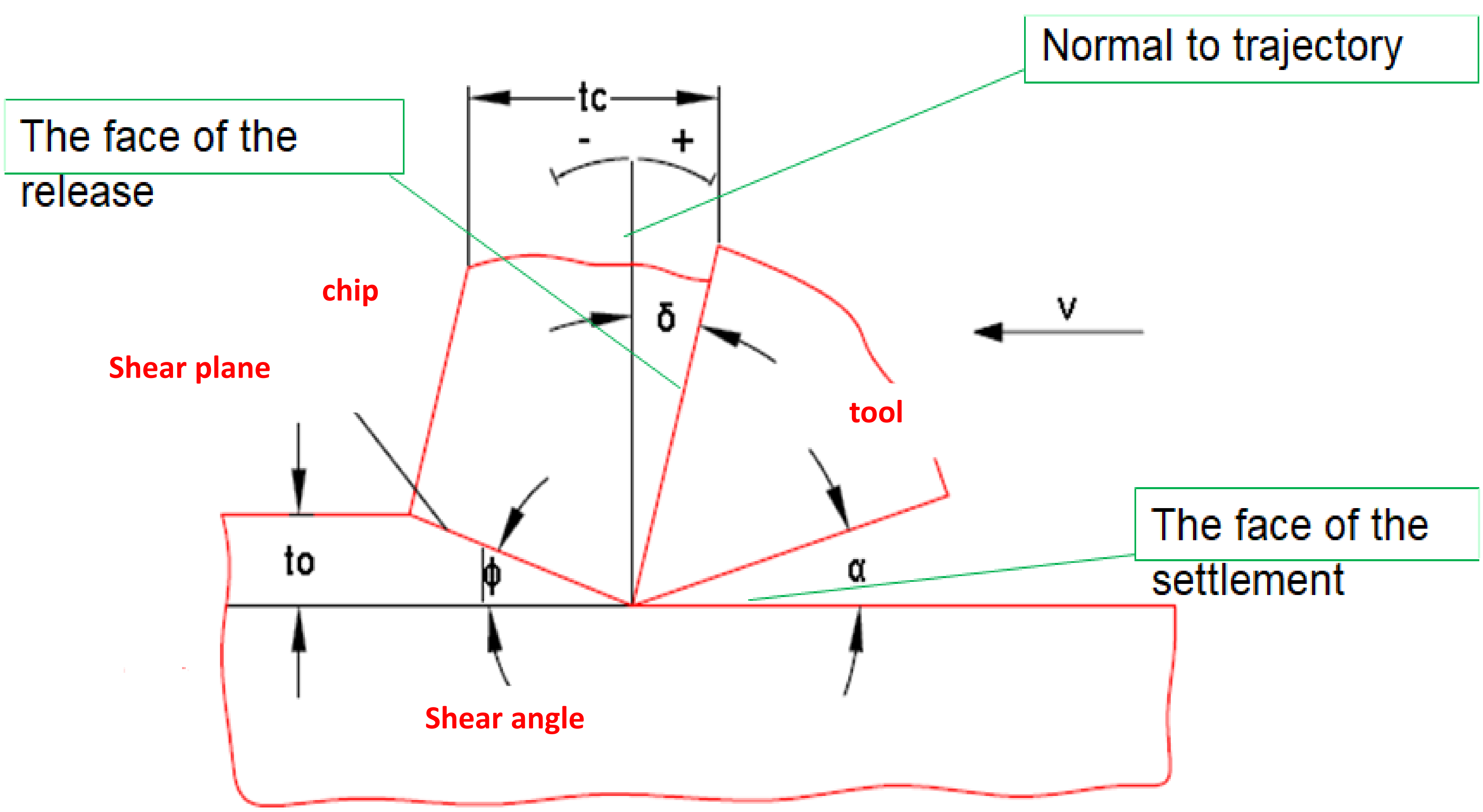


Fig. 1. Orthogonal cutting model [1]

Where:

- v - the speed of the cutting tool;
- t_o - depth of cut;
- t_c - chip thickness;
- ϕ - shear angle;
- δ - clearance angle;
- r - chip thickness ratio;
- α - angle of repose.

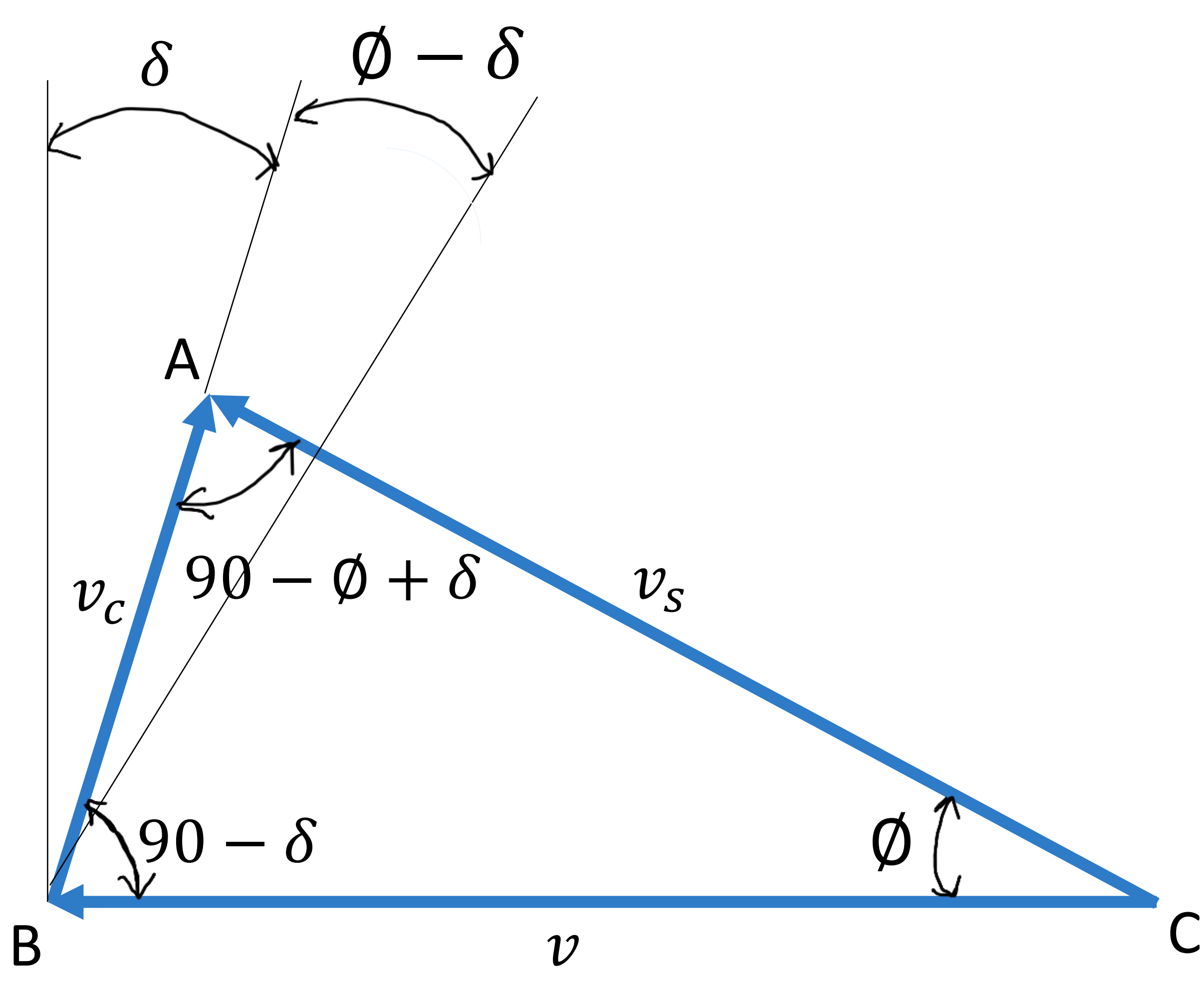


Fig. 2. Speed diagram in the cutting zone [1]

$\Delta ABC \quad m(< C) = \emptyset$

$m(< B) = 90^0 - \delta$

$\longrightarrow m(< A) = 180^0 - [m(< B) + m(< C)] \longrightarrow$

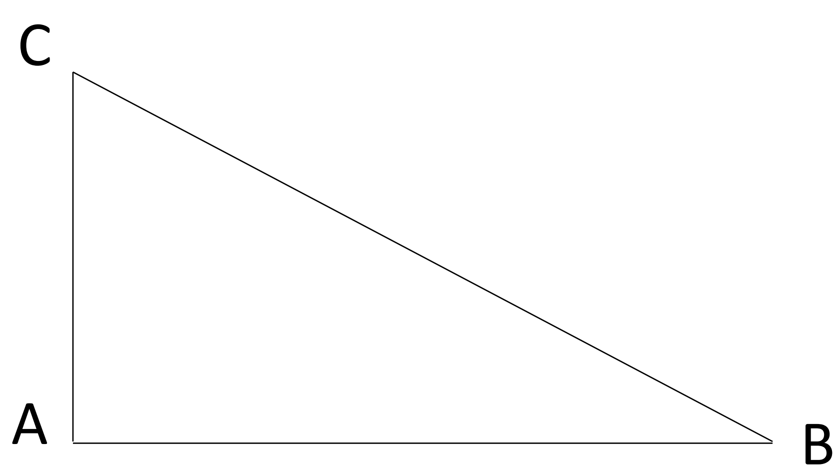
$$\longrightarrow \quad m(< A) = 180^0 - (90^0 - \delta + \emptyset)$$

$$= 180^0 - 90^0 + \delta - \emptyset$$

$$= 90^0 - \emptyset + \delta$$

"The sine theorem" or "The law of sines" applied in triangle ABC is:

$$\frac{AB}{\sin C} = \frac{BC}{\sin A} = \frac{AC}{\sin B}$$



Theory

$$\sin \alpha = \frac{c_{op}}{Ip}$$

$$\cos \alpha = \frac{c_{al}}{Ip}$$

$$\sin B = \frac{AC}{BC} \qquad \sin C = \frac{AB}{BC}$$

$$\cos B = \frac{AB}{BC} \qquad \cos C = \frac{AC}{BC}$$

Conclusion

$$\sin B = \cos C \;\rightarrow \sin B = \cos(90^0 - B)$$

$$\cos B = \sin C \;\rightarrow \sin C = \cos(90^0 - C)$$

or

$$\cos C = \sin(90^0 - C)$$

$$\cos B = \sin(90^0 - B)$$

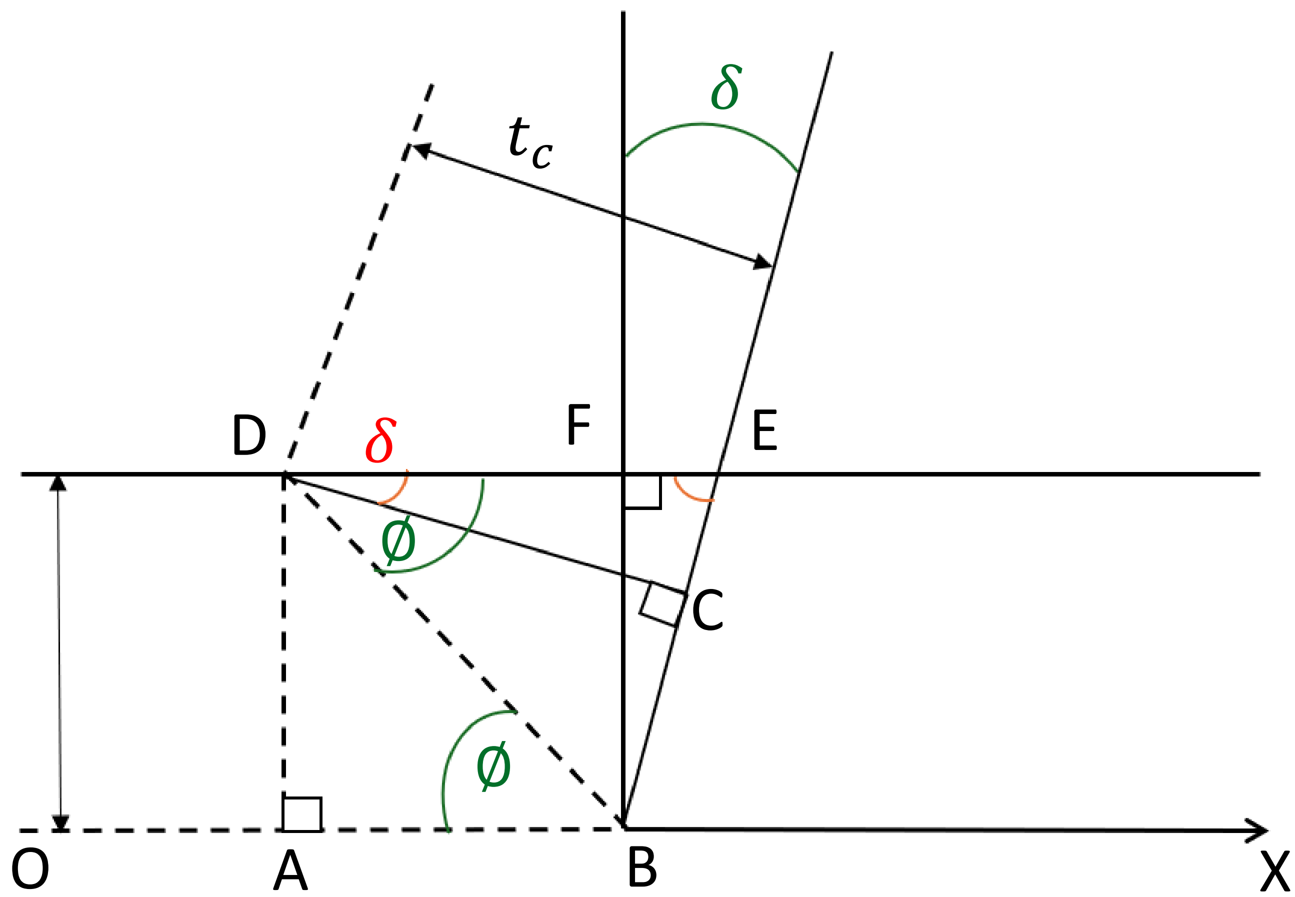
⟶ (1’)

Applying the “Law of Sines” to the figure on slide 18 gives:

$$\frac{v_c}{\sin \emptyset} = \frac{v}{\sin[90^0 - (\emptyset - \delta)]} = \frac{v_s}{\cos \delta} \qquad (1)$$

The relationship (1), using the relationship (1’), becomes:

$$\frac{v}{\cos(\emptyset - \delta)} = \frac{v_c}{\sin \emptyset} = \frac{v_s}{\cos \delta}$$



In ΔDAB, we apply the sine function of angle $\emptyset$

$$\sin\emptyset = \frac{AD}{BD} = \frac{t_0}{BD} \rightarrow t_o = BD \cdot \sin\emptyset \qquad (2)$$

In ΔBFE, it is known that the sum of all angles is $180^0 \rightarrow$

$$\rightarrow \sphericalangle E = 180^0 - 90^0 - \delta$$

In ΔDCE, it is known that the sum of all angles is $180^0 \rightarrow$

$$\rightarrow \sphericalangle D = 180^0 - 90^0 - (90^0 - \delta) \rightarrow$$

$$\rightarrow \sphericalangle D = \cancel{1}80^0 - \cancel{9}0^0 - \cancel{9}0^0 + \delta \rightarrow$$

$$\rightarrow \sphericalangle D = \delta$$

In ΔBCD, we apply the cosine function of angle D

$$m(\sphericalangle BDC) = \emptyset - \delta$$

$$cos(\emptyset - \delta) = \frac{DC}{BD} = \frac{t_c}{BD} \rightarrow$$

$$\rightarrow t_c = BD \cdot \cos(\emptyset - \delta)$$

r – chip thickness ratio

$$r = \frac{t_0}{t_c} = \frac{BD \cdot \sin\emptyset}{BD \cdot cos(\emptyset - \delta)} = \frac{v_c}{v} \qquad (3)$$

$$r = \frac{BD \cdot \sin\emptyset}{BD \cdot cos(\emptyset - \delta)} \rightarrow r \cdot cos(\emptyset - \delta) = \sin\emptyset /: r$$

$$\frac{1}{r} \cdot \sin\emptyset = \cos(\emptyset - \delta)/: \cos\emptyset \ \ (4)$$

Theory $\cos(\emptyset - \delta) = \cos\emptyset \cos\delta + \sin\emptyset \sin\delta \ (4')$

From (4) and (4') $\rightarrow \frac{1}{r}\frac{\sin\emptyset}{\cos\emptyset} = 1 \cdot \cos\delta + \mathrm{tg}\,\emptyset \cdot \sin\delta \ \rightarrow$

$$\rightarrow \frac{1}{r} \cdot \text{tg}\,\emptyset = \cos\delta + \text{tg}\,\emptyset \cdot \sin\delta \rightarrow$$

$$\rightarrow \cos\delta = \frac{1}{r} \cdot \text{tg}\,\emptyset - \text{tg}\,\emptyset \cdot \sin\delta \rightarrow$$

If we take the common factor on tg ∅, it results:

$$\cos\delta = \text{tg}\,\emptyset \cdot \left(\frac{1}{r} - \sin\delta\right)$$

$$\text{tg}\,\emptyset = \frac{\cos\delta}{\left(\frac{1}{r} - \sin\delta\right)} \rightarrow \text{tg}\,\emptyset = \frac{\cos\delta}{\frac{1 - r \cdot \sin\delta}{r}}$$

$$\rightarrow \text{tg}\,\emptyset = \frac{r \cdot \cos\delta}{1 - r\sin\delta} \rightarrow \emptyset = \text{arctg}\frac{r \cdot \cos\delta}{1 - r\sin\delta}$$

2.4 Cutting forces

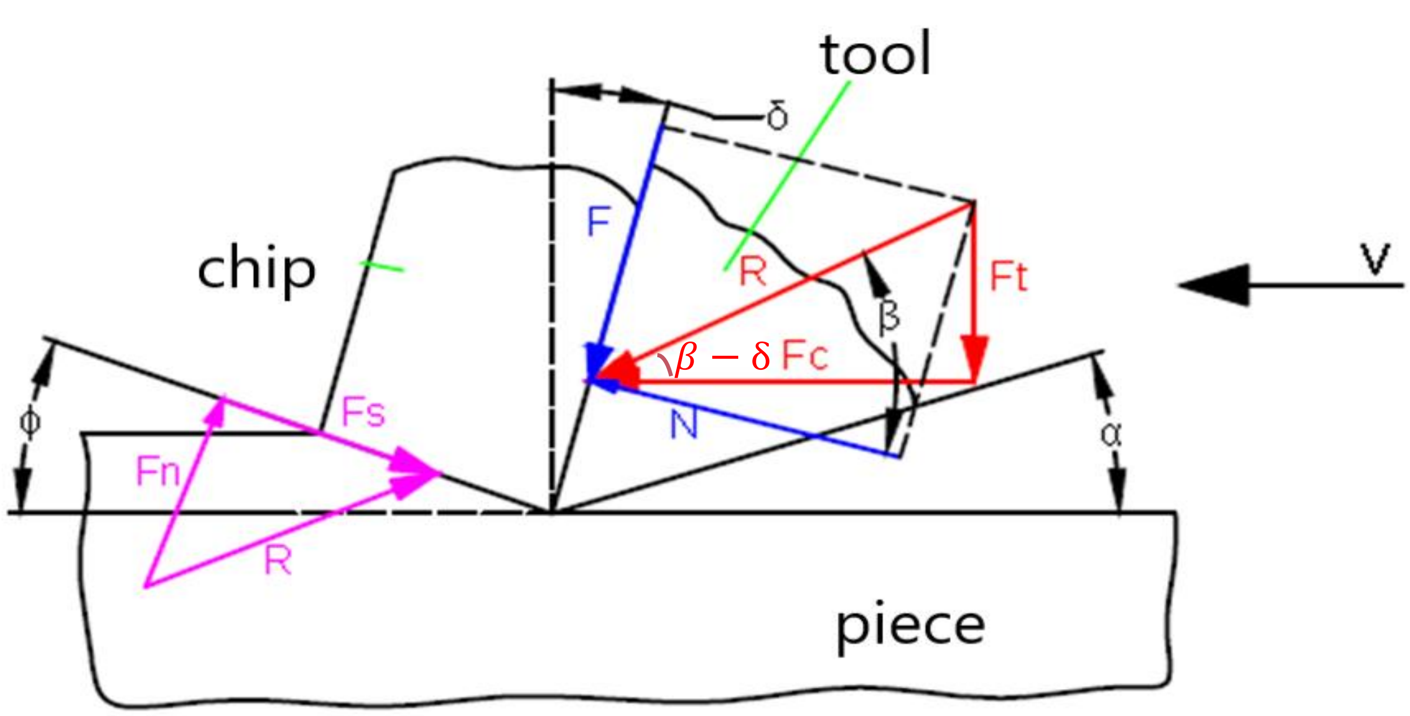


Fig. 3. Cutting forces for orthogonal cutting [1]

$$F = R \cdot \sin\beta \qquad (5)$$

$$N = R \cdot \cos\beta \qquad (6)$$

Where:

β – friction angle

μ - coefficient of friction

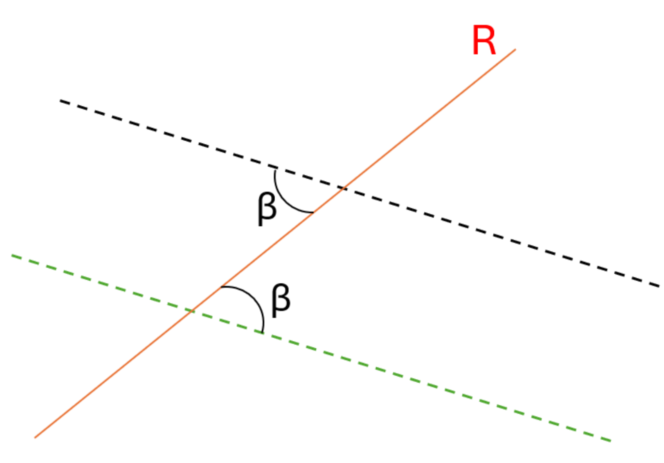
$$\mu = \tan\beta = \frac{F_t + F_c \cdot tan\delta}{F_c - F_t \cdot tan\delta} \qquad (7)$$

$$F_t = R \cdot \sin(\beta - \delta) \qquad (8)$$

$$F_t = F_c \cdot tan(\beta - \delta) \qquad (9)$$

In ΔBAC, we apply the sine function of angle β

β alternate interior angle



$$\sin\beta = \frac{F}{R} \rightarrow F = R \cdot \sin\beta$$

(proof of relation 5)

In ΔBDC, we apply the cosine function of angle β

$$\cos\beta = \frac{N}{R} \rightarrow N = R \cdot \cos\beta$$ (proof of relation 6)

We know that:

$\mu = \frac{F}{N}$ and if we substitute F from relation 5 and N from relation 6, we obtain:

$$\mu = \frac{F}{N} = \frac{R \cdot \sin\beta}{R \ \cdot \cos\beta} = tg\beta$$

In ΔBEC, we apply the sine function of angle $\beta - \delta$

$$\sin(\beta - \delta) = \frac{F_t}{R} \rightarrow F_t = R \cdot \sin(\beta - \delta)$$ (proof of relation 8)

In ΔBEC, we apply the tangent function of angle $\beta - \delta$

$$\mathrm{tg}\ (\beta - \delta) = \frac{F_t}{F_c} \rightarrow F_t = F_c \cdot \mathrm{tg}(\beta - \delta)$$ (proof of relation 9)

Where:

- β – angle of friction
- F_c - cutting force
- v – cutting velocity vector
- F_t - tangential force
- R – resultant force

2.5 Merchant's circle - the case of orthogonal cutting

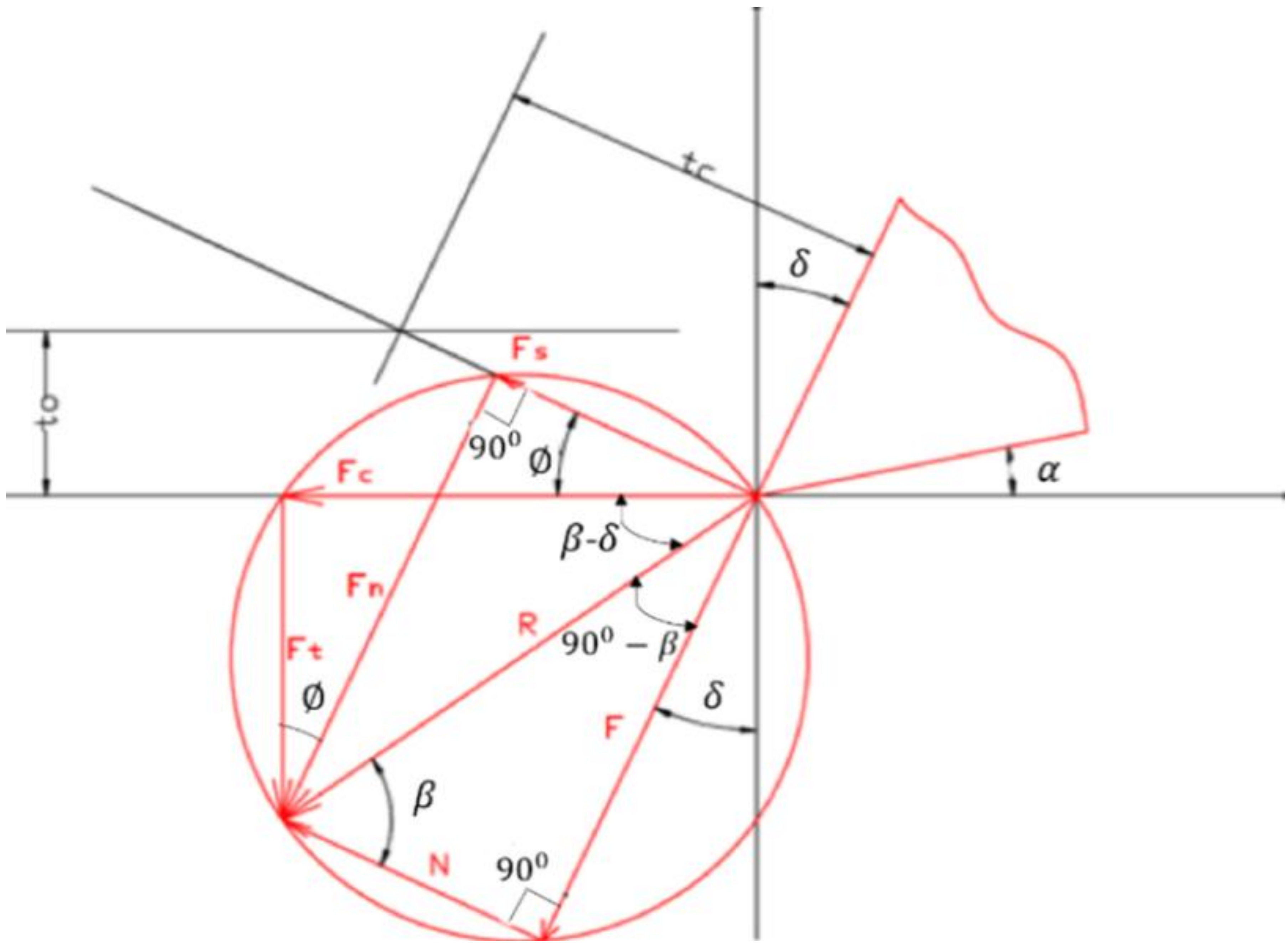


Fig. 4. Merchant's circle of cutting forces [1]

1. Draw the coordinate axis system with the cutting force F_c in the horizontal position (shown in red) and the tangential force F_t in the vertical position (shown in blue). The point of application for the cutting force F_c is at the origin, and the tangential force F_t is positioned with the origin at the tip of F_c.
2. Draw the resultant R of the forces F_c and F_t according to the parallelogram rule.

3. Determine the center of the vector R and draw the circle that includes R (if we draw F_c correctly, F_t, and R will be on the same circle);

4. We extend the line representing the intersection of the clearance face until it intersects the circle, with the resulting segment being marked as F;

5. The vector joining the tip of the frictional force F to the tip of the resultant vector R is the vector N, normal to the clearance face. The angle between N and R is the friction angle β.

$$\text{Vector } R = F_c + F_t = F + N$$

6. Using the chip depth to and the chip thickness t_c, we determine the shear angle θ;

7. From the origin, we draw a vector F_s representing the shear force in the shear plane;

8. Perpendicular to F_s, we draw the vector F_n, joining the tip of F_s to the tip of R.

2.6 Stresses in cutting

Based on the Merchant's circle (fig. 4):

From

$$\Delta OAB \rightarrow \cos(AOB) = \frac{OA}{BO} = \frac{F_c}{R} \rightarrow F_c = R \cdot \cos(\beta - \delta)$$

From

$$\Delta OCB \rightarrow \cos(\emptyset + \beta - \delta) = \frac{OC}{BO} = \frac{F_s}{R} \rightarrow F_s = R \cdot \cos(\emptyset + \beta - \delta) \ (10)$$

We know that: $F_c = R \cdot \cos(\beta - \delta) \rightarrow R = \frac{F_c}{\cos(\beta-\delta)}$ (11)

From (10) and (11) we have:

$$F_s = \frac{F_c}{\cos(\beta - \delta)} \cdot \cos(\emptyset + \beta - \delta)$$

We know that:

$$F_s = R \cdot \cos(\emptyset + \beta - \delta) \rightarrow R = \frac{F_s}{\cos(\emptyset + \beta - \delta)}$$

$$\tau = \frac{F_s}{A_s} \qquad (12)$$

$$\sigma = \frac{F_n}{A_s} \qquad (13)$$

Where:

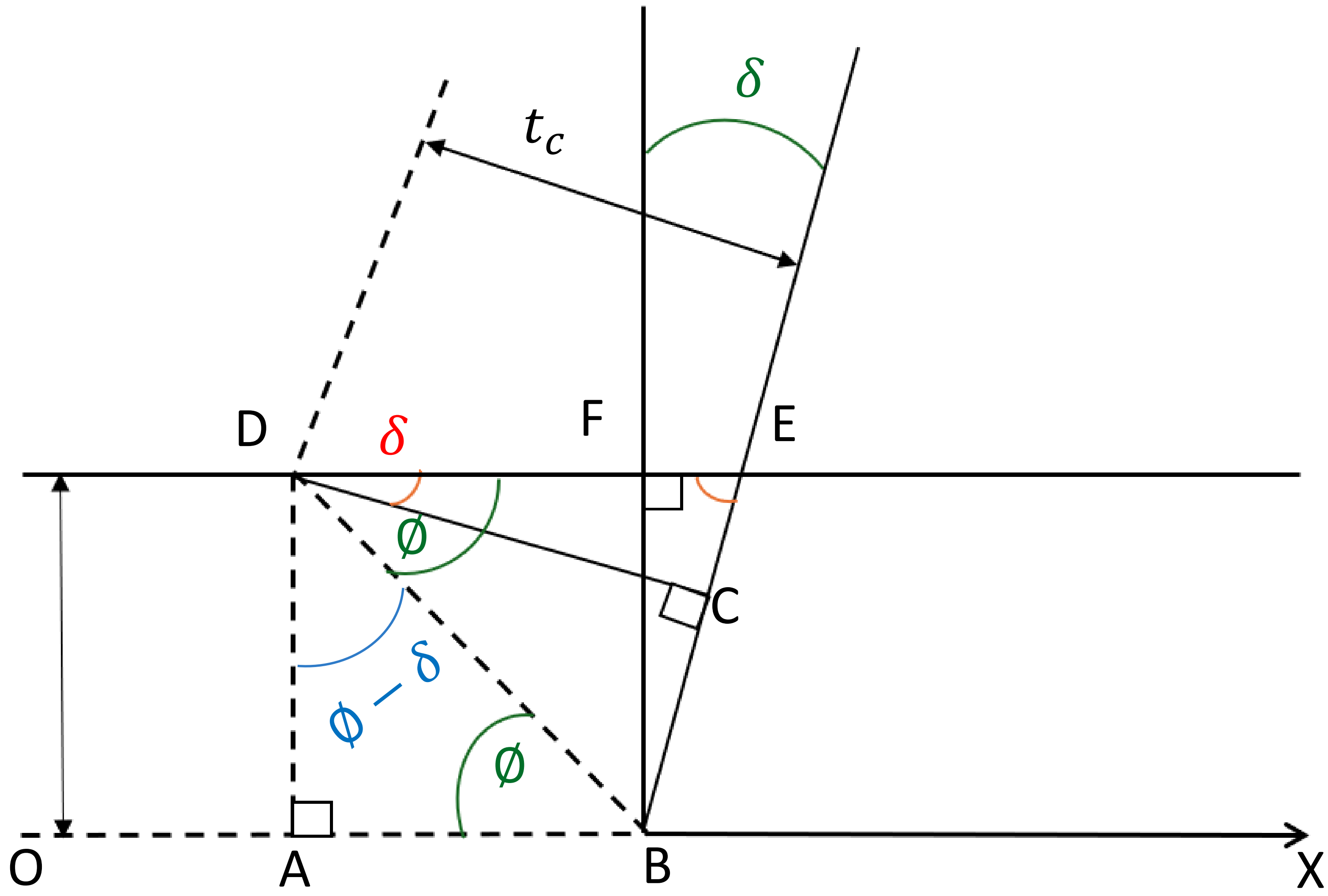
τ - Tangential shear stress, It does not depend on the shear angle

A_s - Shear plane area

F_s - Tangential force

F_n - Normal force

σ - the average value of normal stress



$$\Delta DAB \rightarrow \sin\emptyset = \frac{AD}{BD} = \frac{t_0}{BD} \rightarrow BD = \frac{t_0}{\sin\emptyset}$$

$$A_s = \frac{w \cdot t_0}{\sin\emptyset} \qquad (14)$$

Where:

w – cutting width

t_0 - cutting depth

A_s - shear plan area

Relation 12 becomes:

$$\sigma = \frac{F_s}{A_s} = \frac{\frac{F_c}{\cos(\beta-\delta)} \cdot \cos(\emptyset+\beta-\delta)}{\frac{w \cdot t_0}{\sin\emptyset}}$$

$$\sigma = \frac{F_c \cdot \cos(\emptyset + \beta - \delta) \cdot \sin \emptyset}{w \cdot t_0 \cdot \cos(\beta - \delta)}$$

We differentiate σ with respect to $\emptyset$:

Theory $(f \cdot g)' = f' \cdot g + f \cdot g'$

$$(\cos X)' = -\sin X$$

$$(\cos U)' = -\sin \mathrm{U} \cdot U'$$

$$\frac{d\sigma}{d\emptyset} = \frac{F_c}{w \cdot t_0 \cdot \cos(\beta - \delta)} \cdot [\cos(\emptyset + \beta - \delta) \cdot \sin \emptyset]'$$

constant f g

$$\frac{d\sigma}{d\emptyset} = \frac{F_c}{w \cdot t_0 \cdot \cos(\beta - \delta)} \cdot [-\sin(\emptyset + \beta - \delta) \cdot \sin \emptyset + \cos(\emptyset + \beta - \delta) \cdot cos\emptyset]$$

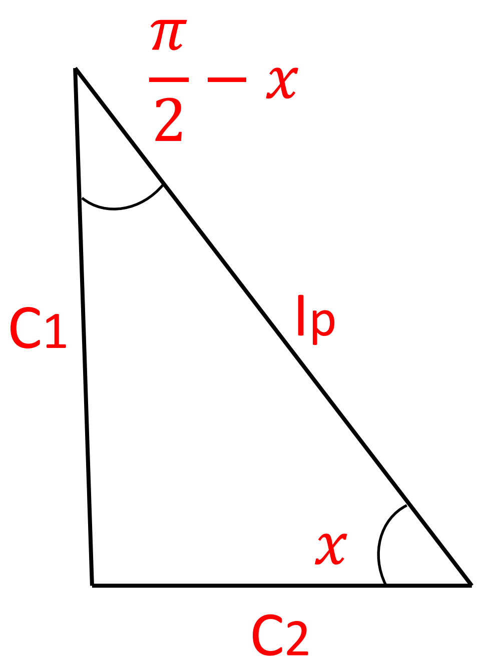
We set the derivative equal to 0

$$\frac{d\sigma}{d\emptyset} = 0 \rightarrow \cos(\emptyset + \beta - \delta) \cdot \cos \emptyset - \sin(\emptyset + \beta - \delta) \cdot \sin \emptyset = 0 \ /:$$

If we divide everything by $[\sin(\emptyset + \beta - \delta) \cdot \sin \emptyset]$

$$\mathrm{ctg}(\emptyset + \beta - \delta) \cdot \mathrm{ctg}\, \emptyset - 1 = 0 \rightarrow \mathrm{ctg}(\emptyset + \beta - \delta) \cdot \mathrm{ctg}\, \emptyset = 1 \qquad (15)$$

Theory



$$\sin x = \frac{C_1}{I_p}$$

$$\cos\left(\frac{\pi}{2} - x\right) = \frac{C_1}{I_p}$$

$$\Longrightarrow$$

$$\sin x = \cos\left(\frac{\pi}{2} - x\right)$$

$$\cos x = \sin\left(\frac{\pi}{2} - x\right)$$

$$\operatorname{ctg} x = \frac{\cos x}{\sin x} = \frac{\sin(\frac{\pi}{2} - x)}{\cos(\frac{\pi}{2} - x)} = \operatorname{tg}\left(\frac{\pi}{2} - x\right)$$

$$ctg = \frac{1}{tg}$$

$$(15) \rightarrow \frac{1}{\operatorname{tg}(\emptyset + \beta - \delta)} \cdot \operatorname{ctg} \emptyset = 1 \rightarrow$$

$$\frac{\operatorname{ctg} \emptyset}{\operatorname{tg}(\emptyset + \beta - \delta)} = 1 \rightarrow \operatorname{tg}(\emptyset + \beta - \delta) = ctg\emptyset$$

$$\operatorname{tg}(\emptyset + \beta - \delta) = \operatorname{tg}\left(\frac{\pi}{2} - \emptyset\right)$$

$$\emptyset + \beta - \delta = \frac{\pi}{2} - \emptyset \rightarrow 2\emptyset = \frac{\pi}{2} - \beta + \delta \ /: 2$$

$$\emptyset = \frac{\pi}{4} - \frac{\beta}{2} + \frac{\delta}{2} \qquad (16)$$

2.7 Specific cutting energy

Power consumed in the cutting process:

$$P = F_c \cdot v \qquad (17)$$

Where:

- F_c - cutting force
- v – cutting speed (vector)

Total specific energy corresponding to the unit volume of removed material u_t:

$$u_t = \frac{F_c \cdot \cancel{v}}{w \cdot t_0 \cdot \cancel{v}} = \frac{F_c}{w \cdot t_0} \qquad (18)$$

The specific energy required to overcome the friction force:

$$u_f = \frac{F \cdot v_c}{w \cdot t_0 \cdot v} = \frac{F \cdot r}{w \cdot t_0} = \frac{(F_c \cdot \sin\delta + F_t \cdot \cos\delta) \cdot r}{w \cdot t_0} \qquad (19)$$

It is observed that the chip thickness t_c is greater than the cutting depth t_o, which causes the speed v_c to be lower than the cutting speed v. It can be written as follows:

$$v \cdot t_0 = v_c \cdot t_c$$

$$r = \frac{t_o}{t_c} \;\Rightarrow\; v_c = \frac{v \cdot t_o}{t_c} \;\Rightarrow\; v_c = v \cdot r$$

Specific shear energy:

$$u_s = \frac{F_s \cdot v_s}{w \cdot t_0 \cdot v} \qquad (20)$$

From Merchant's circle, in Δ AOB, if the sine function is applied to $(\beta - \delta)$ we obtain:

$$\sin(\beta - \delta) = \frac{F_t}{R} \rightarrow F_t = R \cdot sin(\beta - \delta)$$

From Merchant's circle, in Δ AOB, if I apply the sine function to $(\beta - \delta)$ we obtain:

$$\cos(\beta - \delta) = \frac{F_c}{R} \rightarrow F_c = R \cdot cos(\beta - \delta)$$

In Δ ODB if the sine function is applied to β we obtain:

$$sin\beta = \frac{F}{R} \rightarrow R = \frac{F}{sin\beta} \; or \; F = \frac{sin\beta}{R}$$

We substitute *R* in the relationship between F_t and F_c, we obtain:

$$F_t = \frac{F}{sin\beta} \cdot sin(\beta - \delta)$$

$$F_c = \frac{F}{sin\beta} \cdot cos(\beta - \delta)$$

$$\frac{u_f}{u_s} = \frac{F \cdot v_c}{F_c \cdot v} = \frac{(R \cdot sin\beta) \cdot v_c}{\frac{F}{sin\beta} \cdot cos(\beta - \delta) \cdot v} = \frac{R \cdot sin\beta}{\frac{F}{sin\beta} \cdot cos(\beta - \delta)} \cdot \frac{v_c}{v}$$

$$\frac{u_f}{u_s} = \frac{R \cdot sin\beta}{\frac{R \cdot sin\beta}{sin\beta} \cdot cos(\beta - \delta)} \cdot \frac{v_c}{v} = \frac{sin\beta}{cos(\beta - \delta)} \cdot \frac{v_c}{v}$$

It was previously demonstrated that: $t_c = BD \cdot cos(\emptyset - \delta)$ and $t_0 = BD \cdot sin\,\emptyset$

If

$$r = \frac{t_0}{t_c} = \frac{BD \cdot sin\emptyset}{BD \cdot cos(\emptyset - \delta)} = \frac{v_c}{v}$$

$$\frac{u_f}{u_s} = \frac{sin\beta}{cos(\beta - \delta)} \cdot \frac{v_c}{v} = \frac{sin\beta}{cos(\beta - \delta)} \cdot \frac{sin\emptyset}{cos(\beta - \delta)} \qquad (21)$$

Chapter 3. Manufacturing Precision

Processing precision is influenced by a multitude of factors:

1. **Previous Machining:**
   - Dimensional deviation
   - Errors in the shape of the previous machine
   - Mutual positioning between the current setup and the previously machined surface
   - Surface roughness of the previous work
   - Roughened layer
2. **Current Machining:**
   - Kinematic errors from the relative displacements of machine tool sub-assemblies
   - Wear of the technological system (machine, device, tool, part)
   - Elastic deformations of the technological system
   - Thermal deformations of the technological system
   - Vibrations
   - Base and clamping errors
   - Internal stresses.

Allowed Deviations:

1. Dimensions
2. Surface Quality
3. Geometric Shape ⟶ Tolerances
4. Relative Positional Accuracy
5. Condition of the Surface Layer

Actual Deviations Resulting from Processing ⟶ Errors

A properly designed, implemented, and managed technological process ensures that the resulting errors are less than the permissible tolerances.

The sum of errors influencing processing must be less than the allowed errors.

3.1 Factors influencing machining precision

Factors with systematic influence (which can be constant or variable according to a specific law) include:

- Machine tool idle errors;
- Wear and breakage of the cutting tool (or elements of the technological system);
- Thermal deformation of the tool, machine tool, and workpiece;
- Blank clamping errors;
- Profile errors of cutting tools.

Factors with random influence:

- Non-uniformity of machining allowance and material structure;
- Rigidity of the technological system;
- Errors in the installation and fixation of the blank;
- Measurement errors;
- Vibrations;
- These factors are often the most unfavorable and difficult to determine. Their influence is analyzed through statistical analysis and probability theory.

3.2 Classification of processing errors

Total machining error: The difference between the actual value and the design value (as prescribed by the design drawing) can be expressed as:

$$\varepsilon_T = f\left(\varepsilon_0, \varepsilon_f, \varepsilon_r, \varepsilon_p, \varepsilon_m\right) \quad (22)$$

Where:

- ε_0 - Orientation error of the blank or cutting tool
- ε_f - Fixing error
- ε_r- Adjustment error
- ε_p - Processing error
- ε_m - Measurement error

Measurement errors: These errors are determined by the methods and technical means used for measurement, as well as the qualification and skill of the measurer.

Fixing errors: These errors arise from elastic deformations of the blank caused by excessive clamping force in the fixture. Even if the blank is rigid, elastic deformation can still occur at the contact surfaces between the blank and the fixture.

Processing errors inevitably occur during manufacturing and are due to several factors, including:

- Mismatch between the actual and theoretical processing schemes;
- Inaccuracies in machine tool execution;
- Wear of the elements in the technological system;
- Elastic deformations of the technological system;
- Thermal deformations;
- Vibrations;
- Internal stresses;
- Self-vibrations.

3.3 Orientation error

Orientation errors are linear or angular errors that occur due to a mismatch between the orientation and measurement bases.

The magnitude of orientation errors is determined by the extent of variation between the measurement bases and the orientation bases in the measurement direction.

Calculation of orientation error

1. **Identify the fixed element:** Determine the orientation base (B) of the dimension for which the error calculation is performed.

2. **Set the adjustment dimension (CR):** Establish the adjustment dimension (CR) by joining the fixed element to the surface to be machined.

3. **Establishment of the dimension chain**: In the dimensioning chain, both the adjustment dimension (CR) and the dimension for which the orientation error is being calculated must be included:

$$L = f(l) = \sum_{i=1}^{n-1} l_i \qquad (23)$$

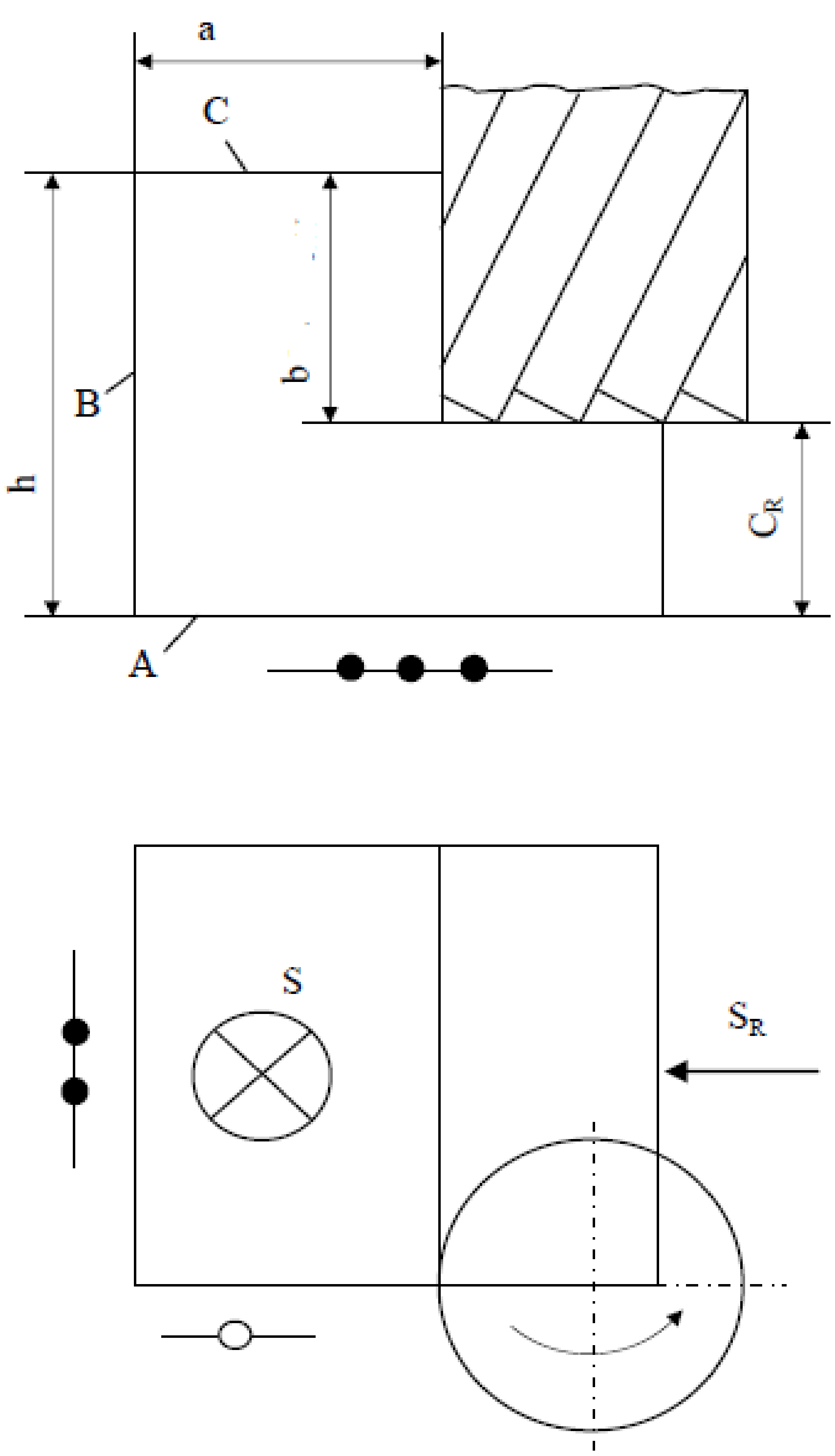


Fig. 5. Cylindrical frontal milling of a prismatic part [1]

After establishing the dimension chain, the computational dimension L is expressed as a function of the other elements in the chain:

- One can express the function that corresponds to the deviations of the chain dimensions as follows:

$$\Delta L = f(\Delta l) = \sum_{i=1}^{n-1} \Delta l_i \qquad (24)$$

- In the case of equation (2), ΔCR =0 (where ΔC_R is the adjustment dimension) indicates that it does not vary from piece to piece within the same size chain.

- In relation (2), substitute the dimensional variations with the specified tolerances to obtain:

$$\varepsilon_0 = f(T_l) = \sum_{i=1}^{n-1} T_{l_i} \qquad (25)$$

- Errors can be summed up probabilistically:

$$\varepsilon_0 = \sqrt{\sum_{i=1}^{n=1} (T_{li})^2} \qquad (26)$$

- The actual calculated orientation errors must be less than the permissible ones

$$\varepsilon_0 < \varepsilon_{0\ adm} \qquad (27)$$

- The permissible values for orientation errors must be within approximately one third of the tolerance value

$$\varepsilon_{0\ adm} = \frac{1}{3}T \qquad (28)$$

3.4 Fastening errors

These errors are caused by elastic deformations of the blanks due to being clamped in the fixture with high clamping forces. These forces are necessary to ensure the immobility of the part during machining. If the blank is rigid, elastic deformations occur at the contact surface between the blank and the clamping pads.

- The process involves applying a small positioning force first, and once the blank is correctly positioned in the fixture, a larger clamping force is applied.
- For a batch of parts, a large dispersion in elastic contact deformation values leads to a greater influence of clamping and clamping errors on machining accuracy.

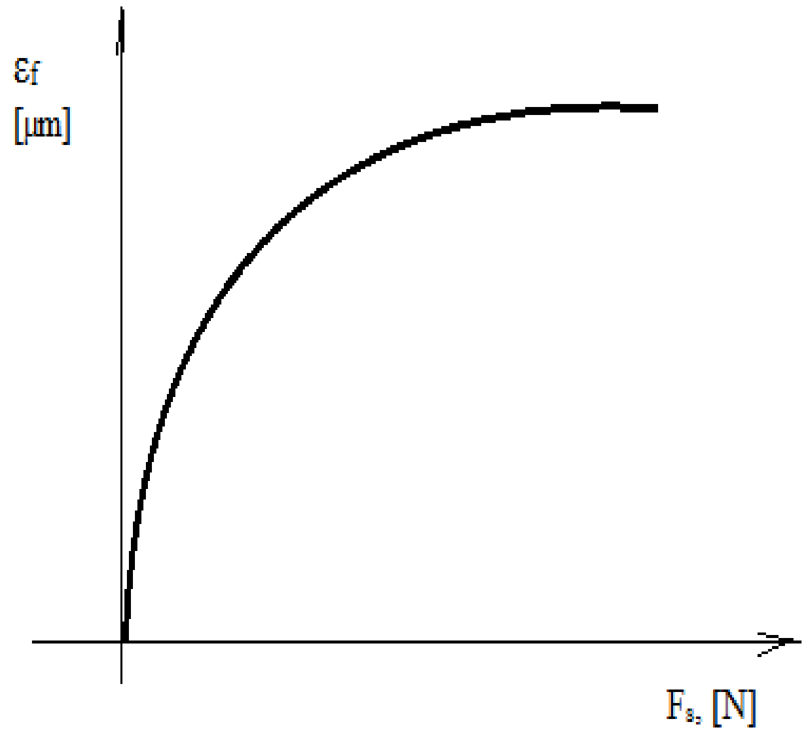


Fig. 6. Diagram of contact strain variation

as a function of clamping force [1]

The magnitude of the deformation is represented by an exponential function:

$$\varepsilon_f = C \cdot F_s^n \quad (29)$$

Where:

- *C* is the material constant;
- F_s is the clamping force;
- *n* is the subunit exponent.

In the case of less rigid semi-finished products (such as thin-walled tubular parts), local elastic deformations inevitably occur in addition to contact deformations.

When the part is released from the fixture, the clamping forces disappear, allowing the blank to return to its elastic state, which results in shape errors of the workpiece.

3.5 Influence of machine tool's geometric accuracy on machining precision

Parameters of geometric accuracy:

- Straightness and parallelism of machine tool guides;
- Flatness of tables;
- Radial runout of the main shafts;
- Coaxiality of various working parts;
- Perpendicularity of various working parts.

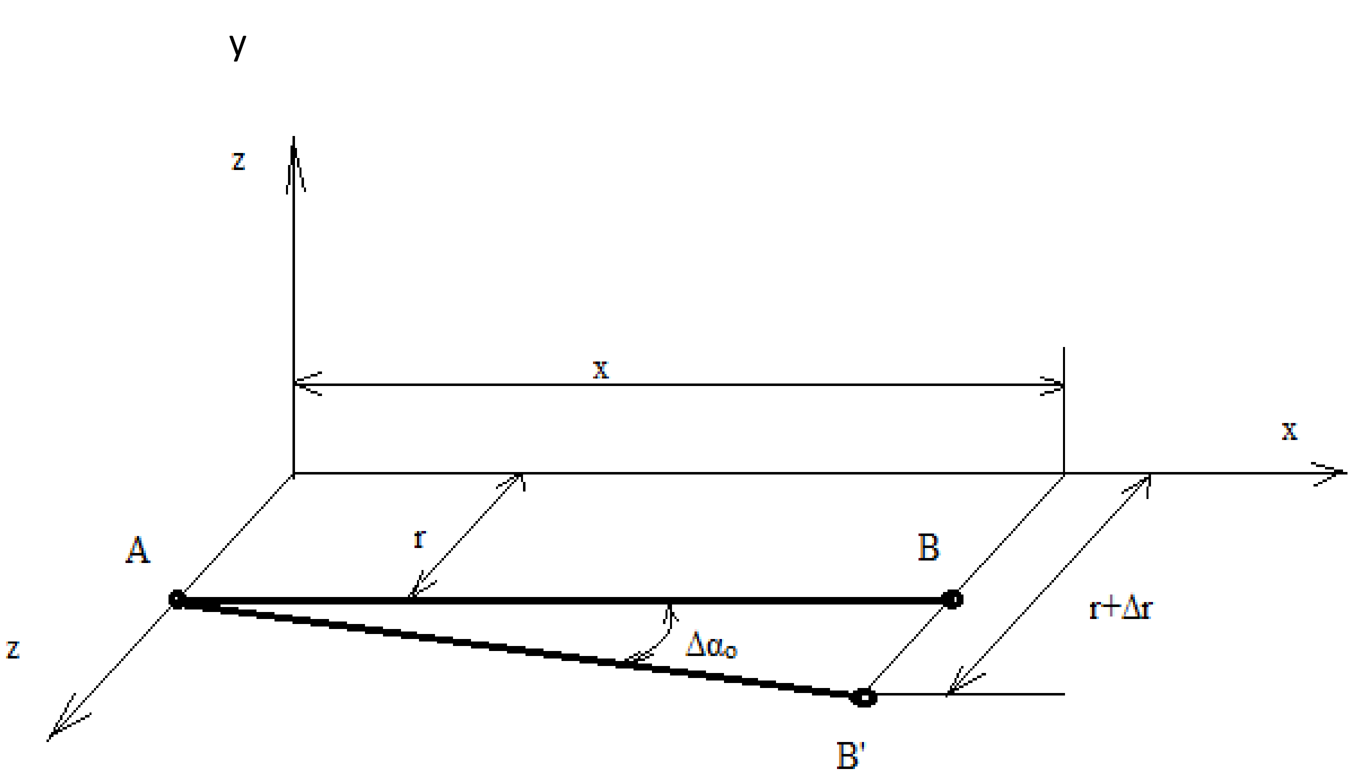


Fig. 7. Deviation from parallelism of the longitudinal guides of the parallel lathe to the axis of the main spindle in the horizontal plane [5]

We consider the OX axis as the axis of the main spindle, while segment AB represents the theoretical (correct) trajectory of the cutting tool tip during machining. If there is a deviation from parallelism between the longitudinal guides of the lathe and the axis of the main spindle, the actual trajectory will follow AB’.

Notations:

OX – axis of the main spindle;

AB – theoretical (correct) trajectory of the cutting tool tip during machining;

AB′ - actual trajectory due to the deviation from parallelism of the longitudinal guides;

x – length of the cylindrical surface

The given equation represents the relationship between the deviation angle Δα0, the deviation in radius Δr, and the length of the cylindrical surface x:

$$\tan(\Delta_{\alpha_0}) = \frac{BB'}{AB} = \frac{\Delta_r}{x} \qquad (30)$$

Solving for Δ_r :

$$\Delta_r = x \cdot \tan(\Delta_{\alpha_0}) \qquad (31)$$

where:

- Δ_r is the radial deviation caused by the misalignment of the longitudinal guides,
- x is the length of the machined cylindrical surface,
- Δ_{α_0} is the angular deviation from parallelism.

maximum diametrical error $\Delta_d = 2 \cdot x \cdot \tan(\Delta_{\alpha_0})$ (32)

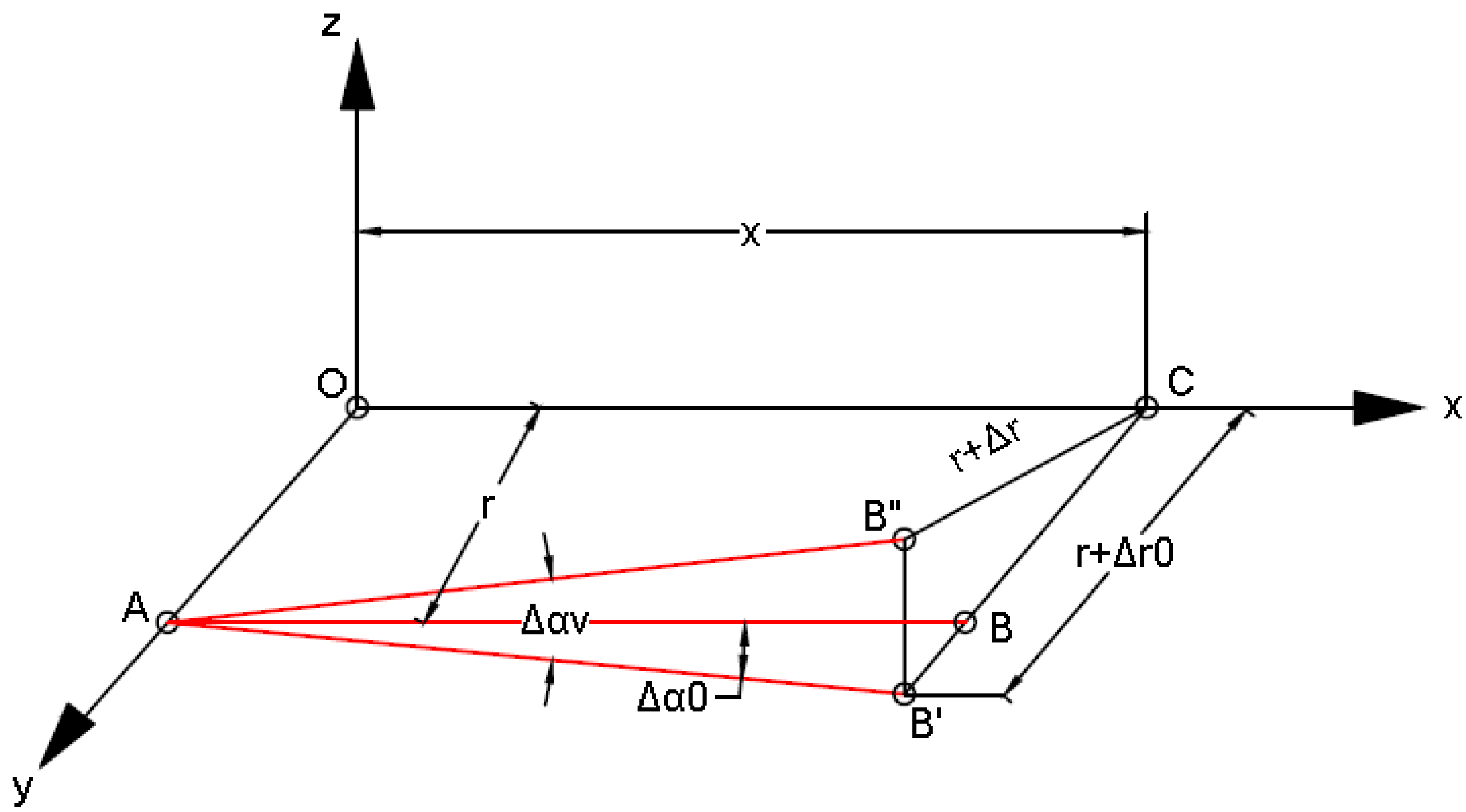


Fig. 8. Deviation from parallelism of the longitudinal guides of the lathe parallel to the axis of the main spindle in the horizontal and vertical plane [5].

From $\Delta ABB'$ we calculate $\sin \alpha_0$

$$sin\ \Delta\alpha_0 = \frac{BB'}{AB'} \rightarrow sin\Delta\alpha_0 \cdot AB' = BB'$$

$$AB' = \frac{BB'}{sin\Delta\alpha_0} \qquad (33)$$

We know that $\Delta r_0 = BB' = x \cdot tg\Delta\alpha_0$ (34)

If we substitute (2) into (1), we obtain: $AB' = \frac{x \cdot tg\Delta\alpha_0}{sin\Delta\alpha_0}$

From $\Delta AB'B''$ we calculate $\text{tg}\ \Delta\alpha_v = \frac{B'B''}{AB'} \Rightarrow\!\!\gg B'B'' = AB' \cdot tg\Delta\alpha_v$ (35)

If we substitute (33) and (34) into (35), we obtain:

$$B'B'' = \frac{x \cdot \operatorname{tg} \Delta\alpha_0}{\sin \Delta\alpha_0} \cdot tg\Delta\alpha_V \qquad (36)$$

From triangle $B''B'C$, based on the Pythagorean theorem, which states that in a right-angled triangle, the sum of the squares of the legs is equal to the square of the hypotenuse.

$$\Rightarrow \underbrace{\left(\frac{x \cdot \operatorname{tg} \Delta\alpha_0}{\sin \Delta\alpha_0} \cdot \operatorname{tg} \Delta\alpha_V\right)^2}_{y} + (r + \Delta r_0)^2 = (r + \Delta r_V)^2 \qquad (37)$$

Equation (5) represents a second-degree equation with the unknown Δr_V

Relation (5) becomes:

$$y^2 + (r + \Delta r_0)^2 = (r + \Delta r_V)^2 \Rightarrow$$

$$\Rightarrow r^2 + 2r\Delta r_V + (\Delta r_V)^2 - r^2 - 2r\Delta r_0 - (\Delta r_0)^2 - y^2 = 0$$

The general form of the second-degree equation:

$$ax^2 + bx + c = 0$$

$$\Delta = b^2 - 4ac \qquad x_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$\Delta = 4r^2 - 4\,[-\,2r\Delta r_0 - (\Delta r_0^2) - \,y^2] = 4r^2 + 4(y^2 + \Delta r_0^2 + 2r\Delta r_0$$

$$\Delta r_{V1,2} = \frac{-2r \pm \sqrt{\Delta}}{2} = -r \pm \frac{2 \cdot \sqrt{\frac{x^2 tg^2 \Delta\alpha_0}{sin^2 \Delta\alpha_0} \cdot tg^2 \Delta\alpha_V + \Delta r_0^2 + 2r\Delta r_0}}{2} \quad (38)$$

3.6 Influence of tool wear on machining accuracy

Tool wear can lead to:

Dimensional deviations in the workpiece.

Deterioration of the rough surface of the machined part.

Increased heat generation in both the tool and the workpiece.

Higher energy consumption during the machining process.

Potential failure or destruction of the cutting edge.

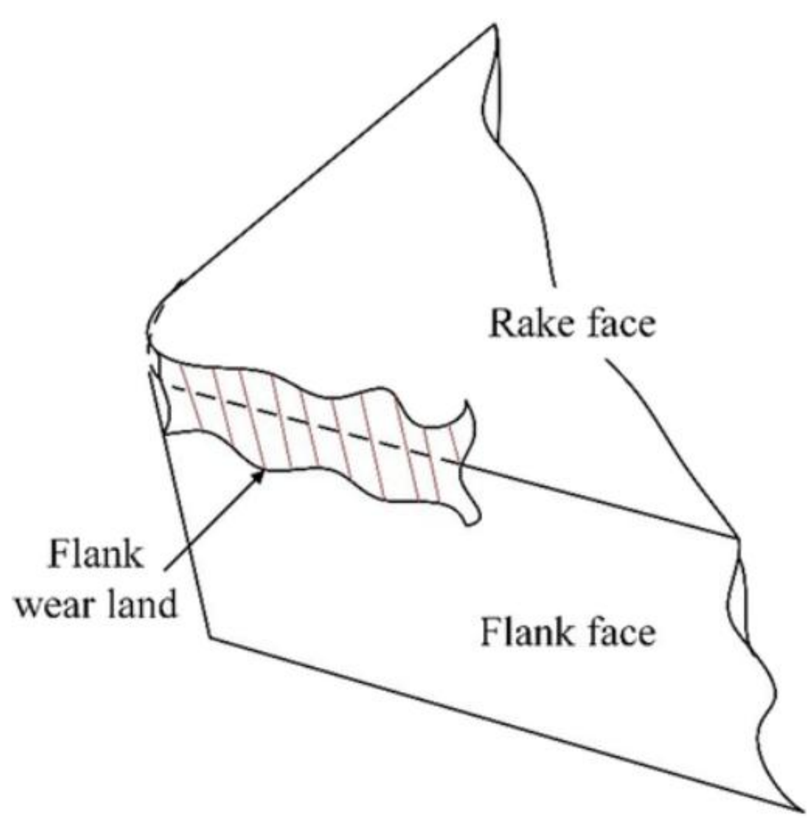


Fig. 9. Schematic representation of crater and flank wear on a cutting tool [8]

3.6.1 Wear on the tool's rake face

Wear on the tool face usually occurs due to friction between the tool and the chip or workpiece during the cutting process. As machining takes place, high temperatures are generated at the contact area. A large portion of this heat is absorbed by the tool material, which can lead to the gradual degradation of its physical and mechanical properties.

Over time, this thermal and mechanical stress results in visible damage, such as **crater wear**, reducing the effectiveness and life of the cutting tool.

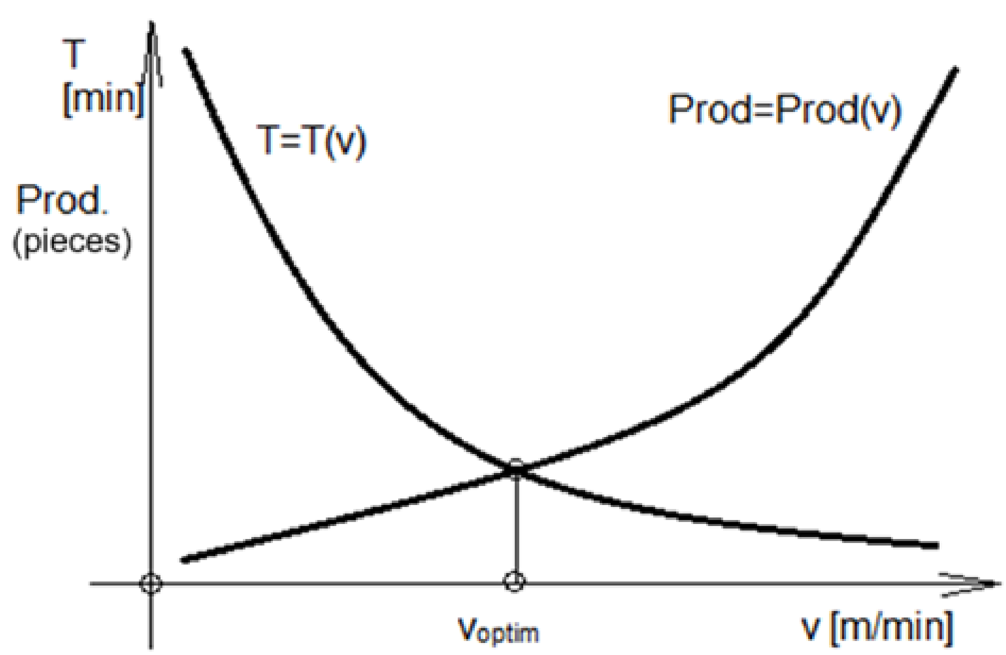


Fig. 10. Dependence of durability on cutting speed and productivity on cutting speed [1].

When machining with high-speed steel (HSS) tools, the recommended cutting speed for steel materials typically ranges between 15 and 40 m/min to ensure optimal tool life and surface finish. In comparison, the recommended cutting speed for carbide tools is between 100 and 300 m/min, depending on the specific carbide grade, machining conditions, and the workpiece material.

3.6.2 Flank wear

Flank wear is a common type of tool wear that occurs on the clearance face of the cutting tool.

The primary factors contributing to flank wear include:

- Mechanical and thermal stress;
- Mechanical abrasion;
- Build-up on the cutting edge;
- Diffusion phenomena;
- Thermal burns;
- Oxidation;
- Thermoelectric currents.

3.6.3 Radial Wear (U-Dimensional Wear)

The greatest influence on dimensional accuracy is caused by wear in the radial direction, which occurs perpendicular to the machined surface.

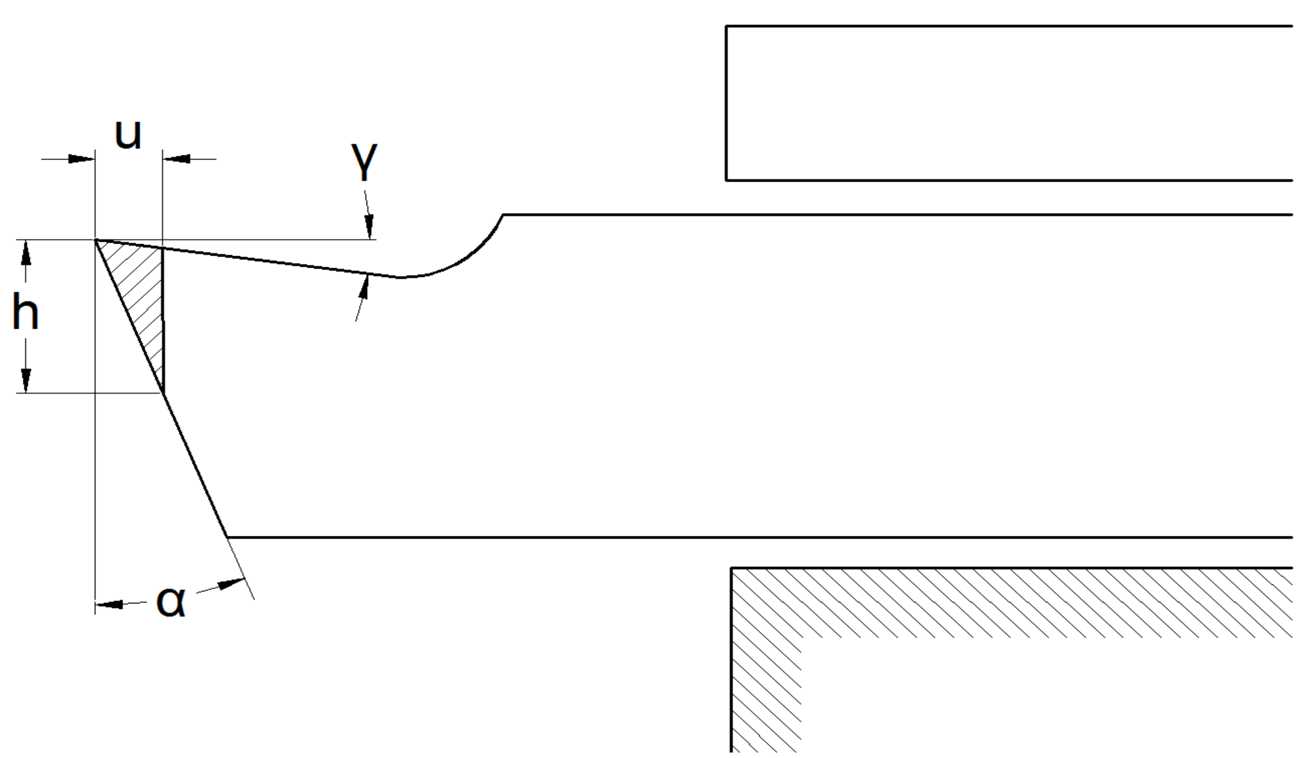


Fig. 11. Tool dimensional wear [4]

Errors of up to 40% can occur because the main cutting edge is not always aligned with the tip of the tool.

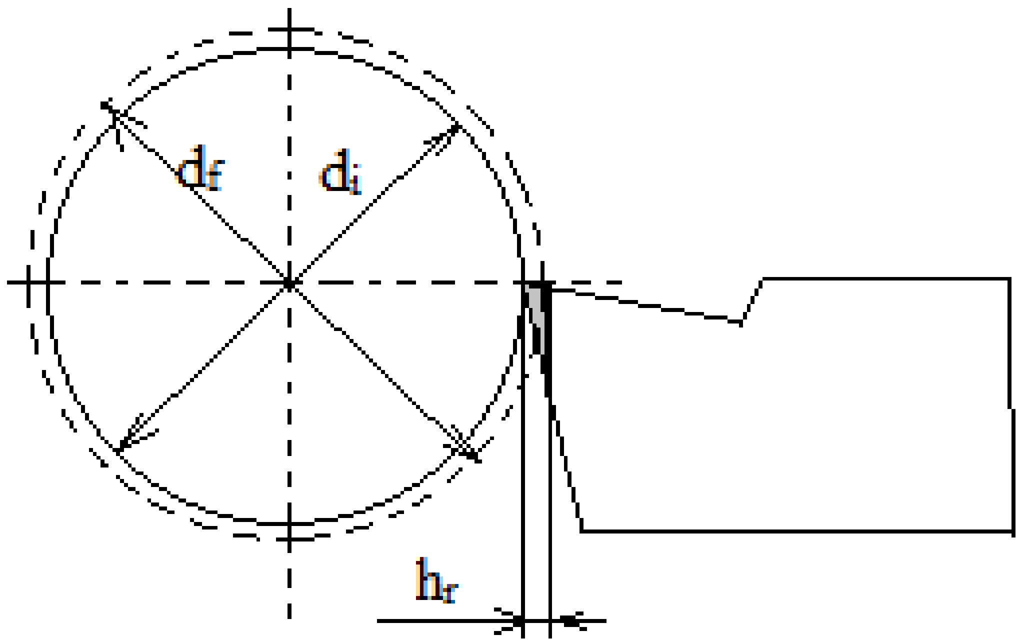


Fig. 12. Influence of tool wear on size processing [4]

- h_r – wear in the radial direction;
- h_α - wear on the clearance face;
- h_γ - wear on the rake face.

$$d_{sf} = d_i + 2 \cdot h_r \qquad (39)$$

Wear can be quantified based on cutting time, the tool's path length on the workpiece, or the total cross-sectional area of material removed from the workpiece.

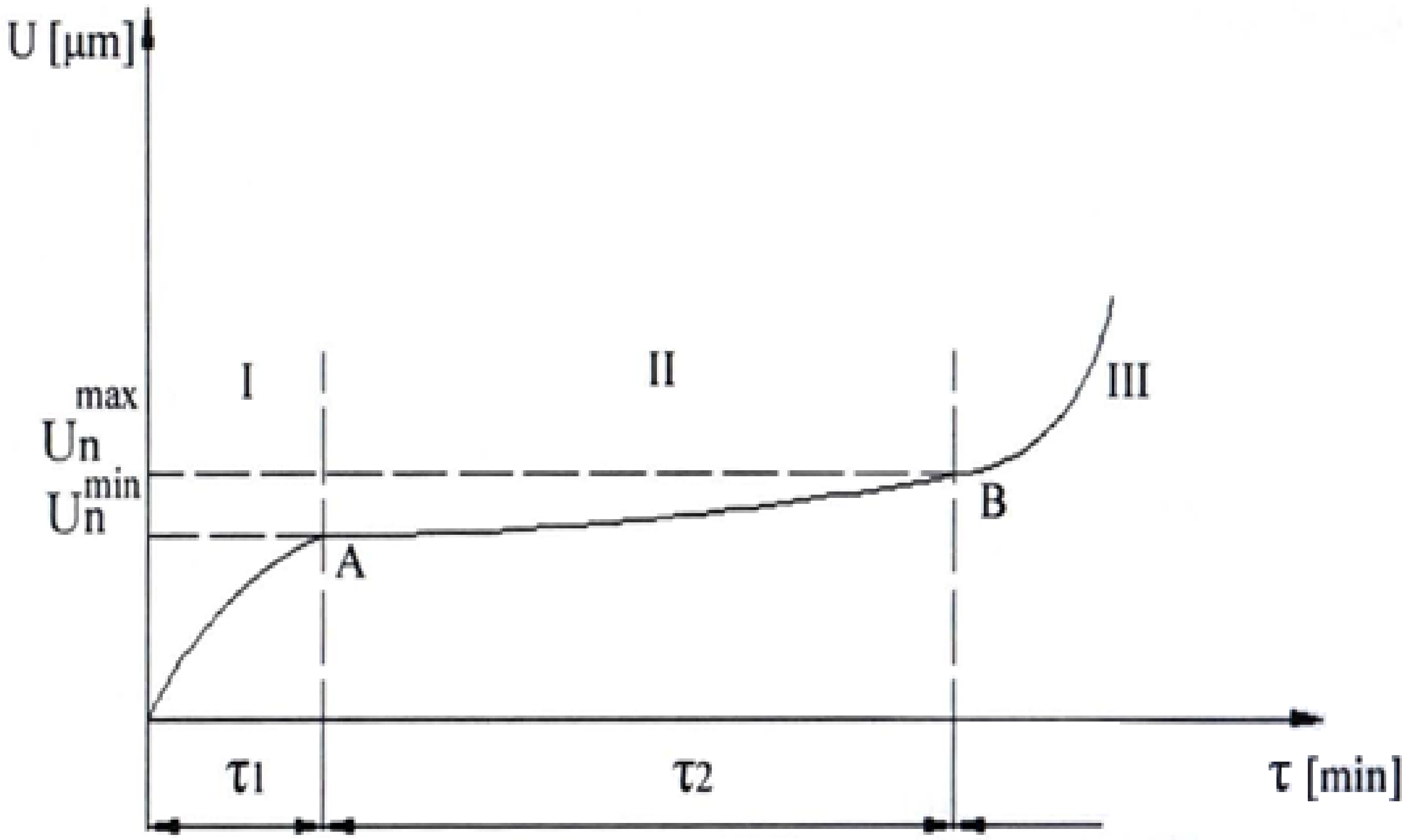


Fig. 13. Dimensional wear vs time diagram [3]

Zone I – Initial High Wear Zone;

Zone II – Stable Wear Zone (Normal Wear);

Zone III – Rapid Wear Zone.

Zone I: Initial wear zone (Break-In Phase)

This phase corresponds to the period during which the micro-irregularities on a new or freshly sharpened tool are smoothed out through initial contact with the workpiece. The wear in this zone reaches up to 5-15 µm and typically occurs over a chipping length of approximately 3000 meters. This break-in process is essential to stabilize the tool before it enters the steady wear phase.

Zone II: Normal wear zone

In this phase, the wear progresses in an approximately linear manner. The tool experiences a consistent and predictable rate of wear, making this zone crucial for defining *relative wear*, which indicates the tool's standard performance over this period. The steady wear behavior in this zone is often used to gauge tool longevity and optimize machining processes.

$$u_r = tg\ \alpha\ [\frac{\mu m}{10^3 m}] \qquad (40)$$

Zone III: Catastrophic wear area

In this final phase, the tool wear rate accelerates dramatically, leading to significant degradation of the tool's cutting edge. At this point, the tool must be sharpened or replaced to maintain machining accuracy and prevent damage to the workpiece or machine. This rapid wear signifies the end of the tool's effective operational life in its current state.

Wear, u, can be expressed as a function of the chipping length L as follows:

$$L = v \cdot \tau \quad (41)$$

In this relationship,

- L represents the cumulative length over which the tool has been engaged in cutting material from the workpiece;
- v represents chip velocity - the speed at which the removed material (chip) moves relative to the cutting tool and the workpiece. This velocity is influenced by factors such as feed rate, tool rotation speed, and the cutting angle. If the chip velocity is too high, it can lead to increased temperature and accelerated tool wear; if it is too low, it may result in inefficient machining. Correctly adjusting the feed rate and cutting speed helps optimize the machining process, balancing efficiency with the durability of the tools used;
- τ represents tool working time - duration during which a cutting tool is actively engaged in material removal on a workpiece. It is a critical metric in machining as it directly affects productivity, tool wear, and overall process efficiency. Optimizing tool working time is essential for balancing efficient production and minimizing tool wear and downtime. Accurate calculations of working time help in scheduling, cost estimation, and tool life management in manufacturing processes.

Specific wear and tear:

$$u_{sp} = \frac{1000 \cdot u}{L} \qquad \left[\frac{\mu m}{1000m}\right] \qquad (42)$$

$$u = u_i + u_{sp}\frac{L}{1000} \qquad [\mu m] \qquad (43)$$

Specific wear and tear refers to the gradual degradation that occurs to machinery, tools, or components over time due to normal use, specifically in a particular way or under certain conditions. In machining, specific wear and tear is an important concept because it focuses on wear patterns or damages that are characteristic of specific processes, materials, or environments. Understanding specific wear and tear helps in selecting appropriate materials, coatings, and machine settings to minimize wear, enhance tool longevity, and improve process stability. Monitoring wear patterns can also inform preventive maintenance schedules, improve equipment uptime and reduce operational costs.

Formula for total length of the cut in Turning or the distance over which the cutting tool travels:

$$L = \frac{\pi \cdot d \cdot l}{1000 \cdot f} \qquad [m] \qquad (44)$$

Where: d - diameter of the machined blank [mm];

l - the length over which the blank is machined [mm];

f – feed rate [mm/rev].

Dimensional wear during the turning process of a shaft results in deviations in diameter. Specifically, the dimensional deviation caused by tool wear can be quantified by the formula:

$$\Delta d = 2u \qquad [\mu m] \qquad (45)$$

Taylor's relationship, often referred to as Taylor's tool life equation, describes the relationship between the cutting speed of a tool and its durability (or tool life). This relationship is fundamental in manufacturing and machining processes, particularly in optimizing cutting conditions for efficiency and cost-effectiveness.

$$T \cdot v^n = C \qquad (46)$$

Where:

• T = Tool life (usually measured in minutes);

• v = Cutting speed (usually measured in meters per minute or feet per minute);

• n = Tool life exponent (a constant that depends on the material being cut and the tool material);

• C = A constant that represents the specific conditions of the machining operation, which includes factors like the tool geometry, workpiece material, and coolant used.

Consider n=0.5 and C=400 to determine the % increase in durability of the chipping tool if the chipping speed is reduced by 50%? [7]

$$v \cdot T^{n} = C \ \rightarrow v \cdot \sqrt{T} = 400 \qquad (47)$$

Since C has the same value in both cases, given relation 48:

$$\begin{aligned} &v_1 \cdot T_1^{0.5} = 400 \ \ si \ \ v_2 \cdot T_2^{0.5} = 400 \ \ \rightarrow \\ &v_1 \cdot \sqrt{T_1} = v_2 \cdot \sqrt{T_2} \rightarrow v_1^2 \cdot T_1 = v_2^2 \cdot T_2 \end{aligned} \qquad (48)$$

Because

$$2 \cdot v_2 \cdot \sqrt{T_1} = v_2 \cdot \sqrt{T_2} \ \ \rightarrow \ \ 2 \cdot \sqrt{T_1} = \sqrt{T_2} \qquad (49)$$

We square equation 49 and get:

$$4 \cdot T_1 = T_2 \ \rightarrow \ \frac{T_2}{T_1} = \frac{4}{1} \qquad (50)$$

$$\frac{T_2 - T_1}{T_1} = \frac{4-1}{1} \qquad (51)$$

The result is that by reducing the cutting speed by 50%, durability of the cutting tool increases by 300%.

3.7 Influence of elastic deformations in the technological system components on machining precision

The elements of the technological system experience movement relative to their initial position, which is defined as the resting state, due to the influence of chipping forces during the machining process. This movement can manifest as displacements in various parts of the system.

The extent of these displacements is influenced by several factors, including the magnitude and direction of the applied stress. Specifically, the type of cutting forces exerted during the machining operation will determine how the individual components of the system respond. Additionally, the ability of these elements to resist deformation under stress plays a crucial role. This resistance depends on the material properties, structural integrity, and design of each component within the technological system.

As the cutting process progresses, the combined effects of stress and the inherent mechanical properties of the elements lead to a dynamic interaction, influencing the overall performance and accuracy of the machining operation. Understanding these relationships is essential for optimizing machining parameters, ensuring both the precision of the final product and the longevity of the tooling and equipment involved.

3.7.1 Static stiffness

Stiffness refers to the ability of a technological system to resist deformation under applied forces that tend to cause changes in shape or position.

It is important to note that the same system can exhibit different resistance levels when subjected to loads from different directions; thus, stiffness is direction-dependent. This means that the stiffness characteristics of a system can vary based on the orientation of the applied force relative to the system's structural layout.

From a mathematical perspective, stiffness (S) is defined as the ratio of the applied force (F_y) to the resulting displacement (y) in the system:

$$S = \frac{F_y}{y}\left[\frac{N}{mm}\right] \qquad (52)$$

• S = stiffness of the system (measured in units such as N/m or lb/in)

• F_y = applied force (in Newtons or pounds)

• y = displacement resulting from the applied force (in meters or inches)

This definition illustrates that a stiffer system will experience less displacement under the same applied force, indicating a higher resistance to deformation. The analysis of stiffness is critical in designing technological systems, as it impacts performance, stability, and accuracy in machining processes.

For the three sub-assemblies of a parallel lathe—namely, the headstock **(HS)**, the tailstock **(TS)**, and the longitudinal saddle **(LS)** - the partial stiffness of each component can be defined as follows:

1. Headstock with main spindle (HS):

1. The stiffness of the headstock is primarily determined by its structural integrity and the rigidity of the main spindle. It provides a stable base for the machining operation and resists deformation under cutting forces. Mathematically, its partial stiffness can be expressed as:

$$S_{HS} = \frac{F_r}{y_{HS}} \left[\frac{N}{mm}\right] \qquad (53)$$

Where F_r is the radial force applied to the fixed puppet and y_{pf} is the resulting displacement.

2. Tailstock (TS):

•The tailstock's stiffness is influenced by its design and the mechanisms that allow for adjustments in position during operation. Its ability to resist deformation is critical for maintaining precision while machining. The partial stiffness of the movable puppet can be defined as:

$$S_{TS} = \frac{F_r}{y_{TS}} \left[\frac{N}{mm}\right] \qquad (54)$$

Where Fr represents the radial force applied to the movable puppet and y_{TS} is the resulting displacement.

3. Longitudinal saddle (LS):

•The longitudinal saddle is responsible for the movement along the workpiece. Its stiffness affects how well it can withstand longitudinal forces during machining. The partial stiffness for the longitudinal sled can be expressed as:

$$S_{LS} = \frac{F_r}{y_{LS}}\left[\frac{N}{mm}\right] \qquad (55)$$

Where F_r is the radial force acting on the saddle and y_{LS} is the associated displacement.

Total stiffness

Total stiffness of a mechanical system refers to the overall resistance of the system to deformation when subjected to external forces. In the case of a parallel lathe, total rigidity is the cumulative effect of the partial stiffnesses of its sub-assemblies: the headstock with the main spindle, the tailstock, and the longitudinal saddle.

Mathematically, total rigidity can be represented as the reciprocal of total compliance (which is the measure of how much a structure deforms under load). If the system, the total rigidity S_{THS} can be calculated as follows:

$$S_{THS} = \frac{F_r}{y_{TS} + y_{LS}}\left[\frac{N}{mm}\right] \qquad (56)$$

The reverse of rigidity is referred to as **compliance**. Compliance is a measure of how much a structure or component deforms under applied forces. It quantifies the flexibility of a system, contrasting with rigidity, which measures resistance to deformation.

Compliance *(W)* is mathematically defined as the inverse of stiffness *(S)*. The relationship can be expressed as:

$$W = \frac{y}{F_r}\left[\frac{mm}{N}\right] \qquad (57)$$

- W = compliance (measured in units such as *m/N*);
- *S* = stiffness (measured in units such as *N/m*);
- y = displacement (measured in units such as *mm*).

The compliance refers to the extent to which a component, system, or material fails to perform its intended function due to deformation, fracture, fatigue, or other forms of degradation. It is a critical concept in engineering and materials science, as it helps assess the reliability, safety, and performance of structures and mechanical systems.

Determination of the **static stiffness** of lathe subassemblies

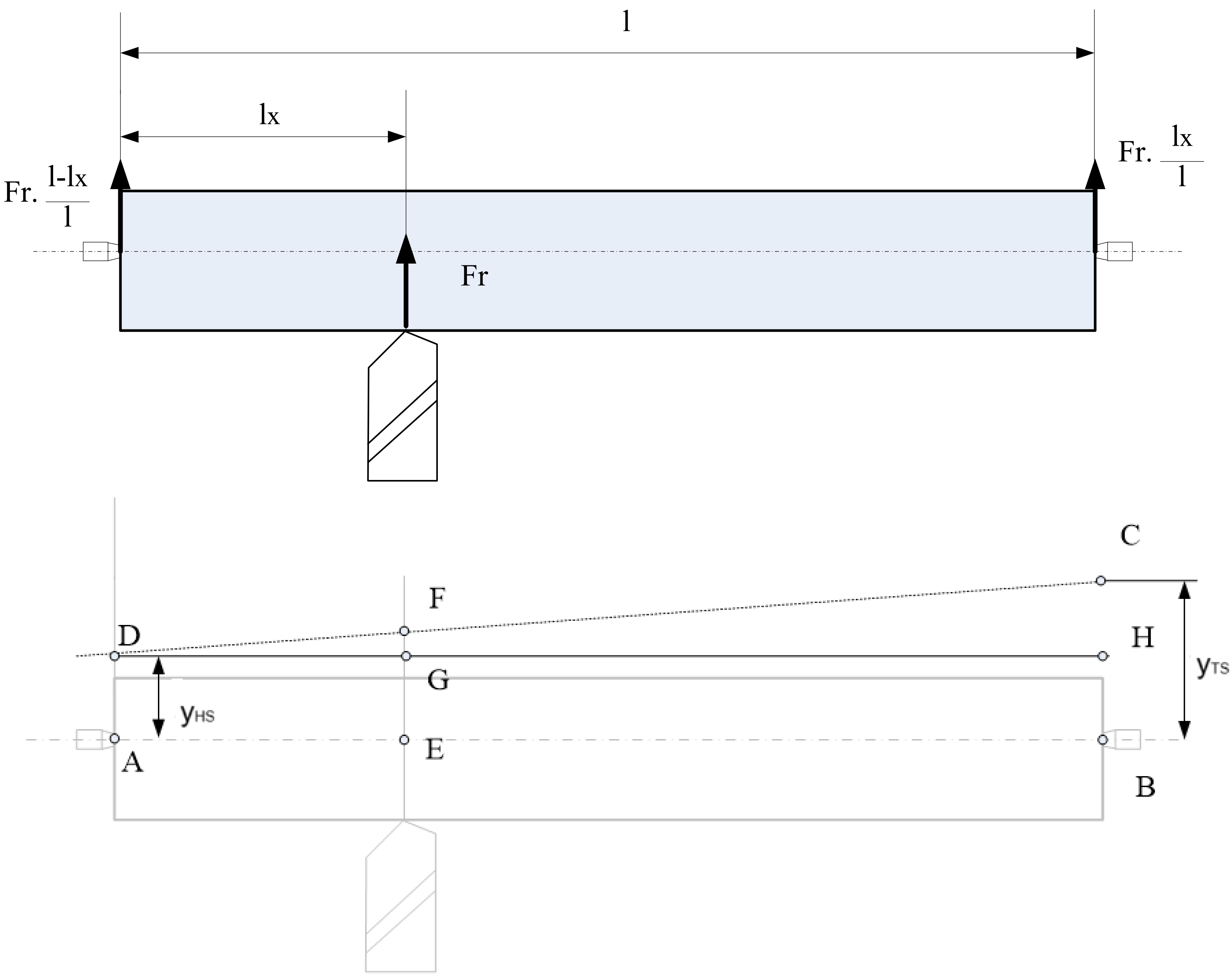


Fig. 14. Scheme for determining total stiffness

(turning - general case) [1]

From the similarity of triangles DFG and CDH, the following proportions are obtained:

$$\left.\begin{array}{l} \frac{FG}{CH} = \frac{DG}{DH} \\ CH = y_{TS} - y_{HS} \\ DG = l_x \\ DH = l \end{array}\right\} \quad (57) \quad \rightarrow \frac{FG}{y_{TS} - y_{HS}} = \frac{l_x}{l} \quad (58) \rightarrow$$

$$\rightarrow \quad FG \cdot l = l_x \cdot (y_{TS} - y_{HS})/: l \qquad (59)$$

$$\rightarrow FG = \frac{l_x}{l}(y_{TS} - y_{HS}) \qquad (60)$$

We express $EF = FG + y_{HS}$ (61)

$$EF = \frac{l_x}{l}(y_{TS} - y_{HS}) + y_{HS} \rightarrow$$

$$EF = \frac{l_x}{l} \cdot y_{TS} - \frac{l_x}{l} \cdot y_{HS} + y_{HS} \rightarrow$$

$$EF = \frac{l_x}{l} \cdot y_{TS} + y_{HS} \cdot \frac{1 - l_x}{l} \rightarrow$$

$$EF = \frac{l_x}{l} \cdot y_{TS} + \left(\frac{l - l_x}{l}\right) \cdot y_{HS}$$

If relationships are taken into account:

$$\begin{cases} y_{HS} = \dfrac{l - l_x}{l} \cdot W_{HS} \cdot F_r \\ y_{TS} = \dfrac{l_x}{l} \cdot W_{TS} \cdot F_r \\ y_{LS} = W_{LS} \cdot F_r \end{cases} \tag{62}$$

You get:

$$y_{T(l_x)} = \frac{l_x}{l} \cdot \frac{l_x}{l} \cdot F_r \cdot W_{TS} + \frac{l - l_x}{l} \cdot \frac{l - l_x}{l} \cdot F_r \cdot W_{HS} + F_r + W_{LS} \tag{63}$$

$$y_{T(l_x)} = \left(\frac{l_x}{l}\right)^2 \cdot F_r \cdot W_{TS} + \left(\frac{l-l_x}{l}\right)^2 \cdot F_r \cdot W_{HS} + F_r \cdot W_{LS} \tag{64}$$

$$W_{HS} = \frac{y_{HS}}{F_r}$$

$$W_{TS} = \frac{y_{TS}}{F_r}$$

$$W_{LS} = \frac{y_{LS}}{F_r}$$

$$y_{T(l_x)} = \left(\frac{l_x}{l}\right)^2 \cdot F_r \cdot \frac{y_{TS}}{F_r} + \left(\frac{l-l_x}{l}\right)^2 \cdot F_r \cdot \frac{y_{HS}}{F_r} + F_r \cdot \frac{y_{LS}}{F_r}$$

$$y_{T(l_x)}=\left(\frac{l_x}{l}\right)^2 \cdot y_{TS} + \left(\frac{l-l_x}{l}\right)^2 \cdot y_{HS} \cdot +y_{LS} \qquad (65)$$

Or:

$$W_{T(l_x)} = \left(\frac{l_x}{l}\right)^2 \cdot W_{TS} + \left(\frac{l-l_x}{l}\right)^2 \cdot W_{HS} + W_{LS} \qquad (66)$$

Hence:

$$\frac{1}{S_{T(l_x)}} = \frac{1}{S_{LS}} + \left(\frac{l_x}{l}\right)^2 \cdot \frac{1}{S_{TS}} + \left(\frac{l-lx}{l}\right)^2 \cdot \frac{1}{S_{HS}} \qquad (67)$$

The rigidity of each component within the technological system significantly influences its overall accuracy. The stiffness of the individual components is defined as follows:

•S_{MT}: Stiffness of the machine tool;

•S_{WCD}: Stiffness of the workpiece clamping device;

•S_{WP}: Stiffness of the workpiece;

•S_{CTHD}: Stiffness of the cutting tool holding device;

•S_{CTR} : Stiffness of the cutting tool rigidity.

The overall stiffness of the technological system (S_{ST}) can be determined using the following relationship:

$$\frac{1}{S_{ST}} = \frac{1}{S_{MT}} + \frac{1}{S_{WCD}} + \frac{1}{S_{WP}} + \frac{1}{S_{CTHD}} + \frac{1}{S_{CTR}} \qquad (68)$$

or

$$W_{ST} = W_{MT} + W_{WCD} + W_{WP} + W_{CTHD} + W_{CTR} \qquad (69)$$

3.7.2 Analytical and experimental determination of dynamic stiffness

The determination is carried out under specific machining conditions, taking into account the actual forces and deformations occurring during the operation of the machine tool (MT). This can be achieved through three methods:

1. Direct measurement of deformation during the cutting process;
2. System excitation using variable forces, followed by recording the resulting deformations;
3. Cutting of specimens with variable chip sections and the calculation of stiffness based on shape errors observed during processing (an analytical-experimental method):

•This approach yields acceptable results for simple geometries, such as shafts (smooth or stepped).

•However, for parts with complex shapes or assemblies, the calculations become challenging, and the results are often unsatisfactory.

•For parts with complex shapes or assemblies, the calculations become more complicated, often leading to unsatisfactory results.

3.8 Technological measures for minimizing errors due to insufficient stiffness in machine tools

The stiffness of the MT can be increased through the following methods:

1. Redesign of the unit;
2. Determining the magnitude of the elastic deformation of the MU under dynamic conditions and incorporating this value into the adjustment calculations to account for deformation during operation.
3. Determining the optimal cutting regime where the magnitude of elastic deformation during machining remains within permissible limits.

Rigidity of the workpiece

The rigidity of the blank significantly affects the total machining error, especially in workpieces with a high length-to-diameter ratio.

•**Elastic deformation:** The workpiece undergoes elastic deformation under the action of cutting forces.

•**Impact of stiffness:** Lower stiffness leads to greater errors, manifested as larger displacements.

Key influences:

1.Geometric accuracy of the surface shape;

2.Dimensional accuracy of the final part.

Calculation of the rigidity of the workpiece

The rigidity of a workpiece refers to its resistance to deformation under applied forces or loads. It is determined by several factors, including material properties, geometry, and boundary conditions. Rigidity is typically quantified in terms of **stiffness** or **modulus of elasticity** for material properties and can also involve the structural response such as deflection or bending.

a. Workpiece clamped between centers

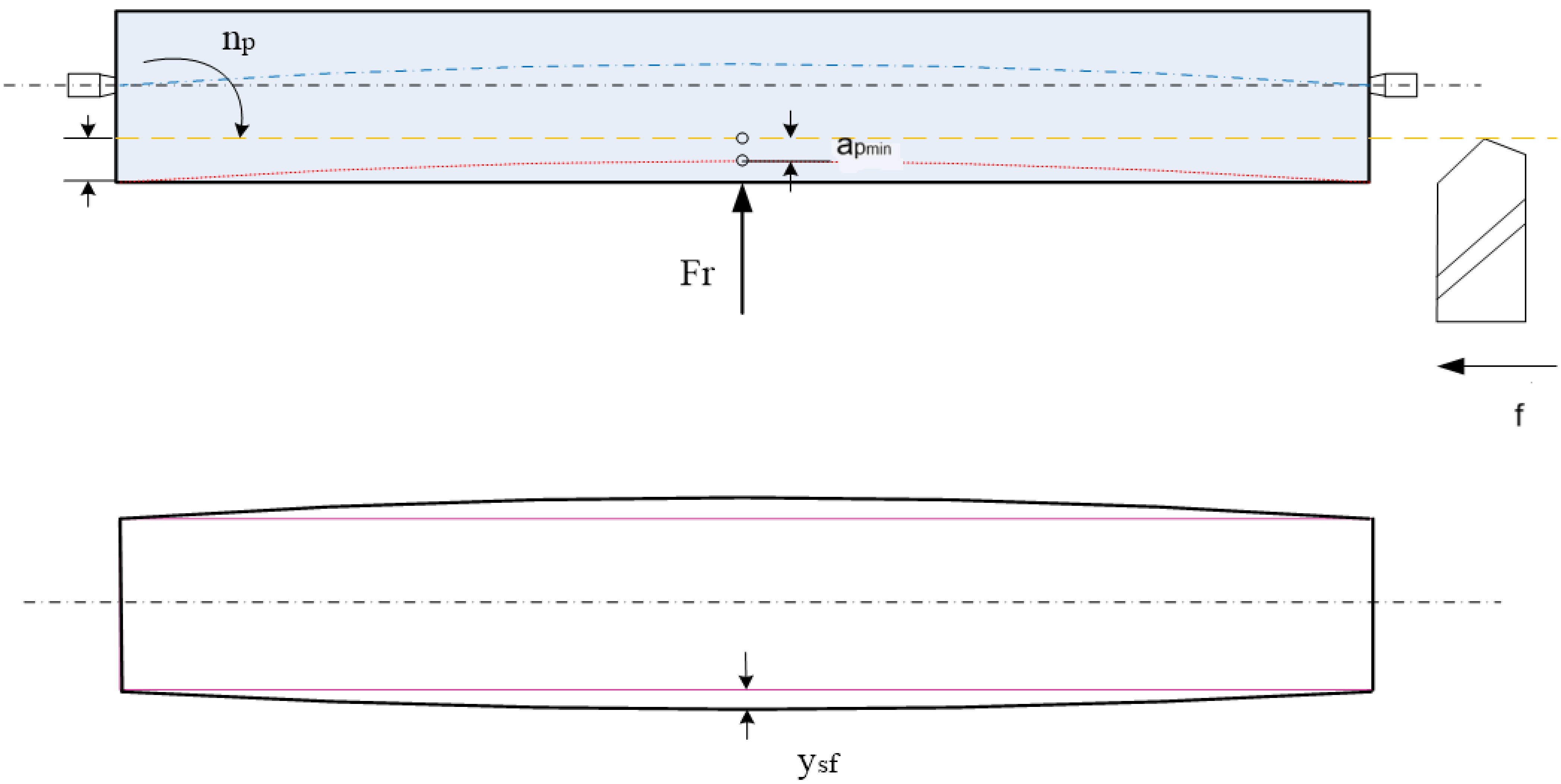


Fig. 15. Clamping between centers [1]

Maximum deflection (y_{sf}):

$$y_{sf} = \frac{F_r \cdot l^3}{48 \cdot E \cdot I} \qquad (70)$$

Rigidity of the workpiece (S_W):

$$S_W = \frac{F_r}{y_{sf}} = \frac{48 \cdot E \cdot I}{l^3} \qquad (71)$$

Where:

F_r – radial component of the cutting force [N];

l– length of the workpiece clamped between centers [mm];

E – modulus of elasticity of the workpiece material [N/mm^2];

I – moment of inertia of the workpiece [mm^4].

b. Workpiece clamped in chuck

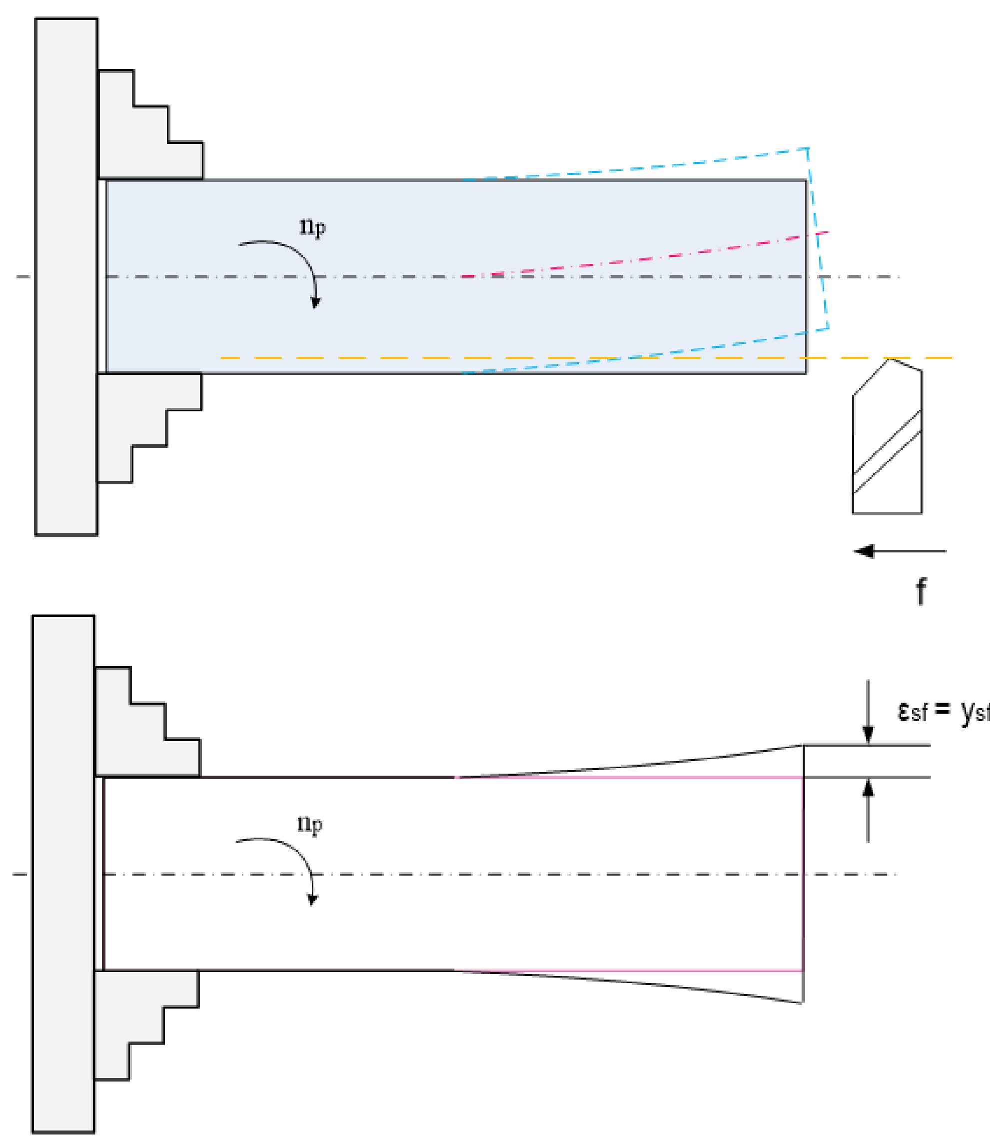


Fig. 16 Workpiece– cantilever mounting [1]

Maximum arrow: $$y_{sf} = \frac{F_r \cdot l^3}{3 \cdot E \cdot I} \quad (72)$$

Rigidity of the workpiece: $$S_W = \frac{F_r}{y_{sf}} = \frac{3 \cdot E \cdot I}{l^3} \quad (73)$$

F_r -radial component of the chipping force [*N*];

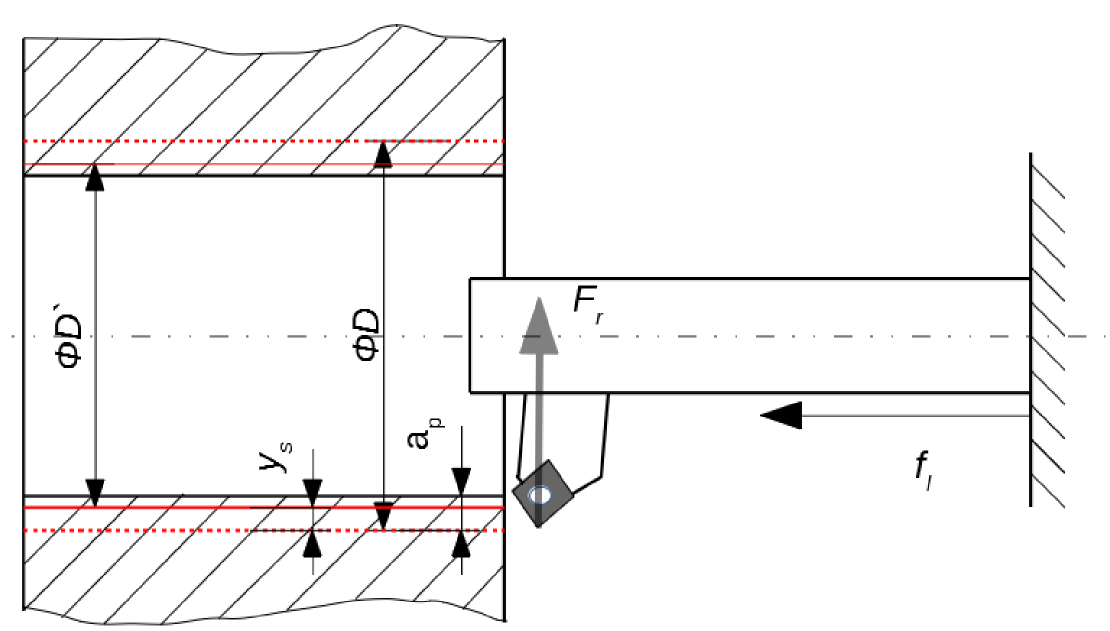
l- the length of the blank clamped between the points [*mm*];

E - modulus of elasticity of the blank material [*N*/mm^2];

I - moment of inertia of the workpiece [mm^4].

3.9 Tool and tool holder rigidity

- Tools and their fixtures are elements of the technological system that are frequently changed according to technological needs => change in the rigidity of the technological system



$$y_{sa} = \frac{F_r \cdot l^3}{3 \cdot E \cdot I} \quad [mm] \quad (74)$$

$$\varepsilon_{sf} = 2 \cdot y_{sa} \quad [mm] \quad (75)$$

Fig. 17. Deformation of the cutting tool shank when clamping in the bracket [5]

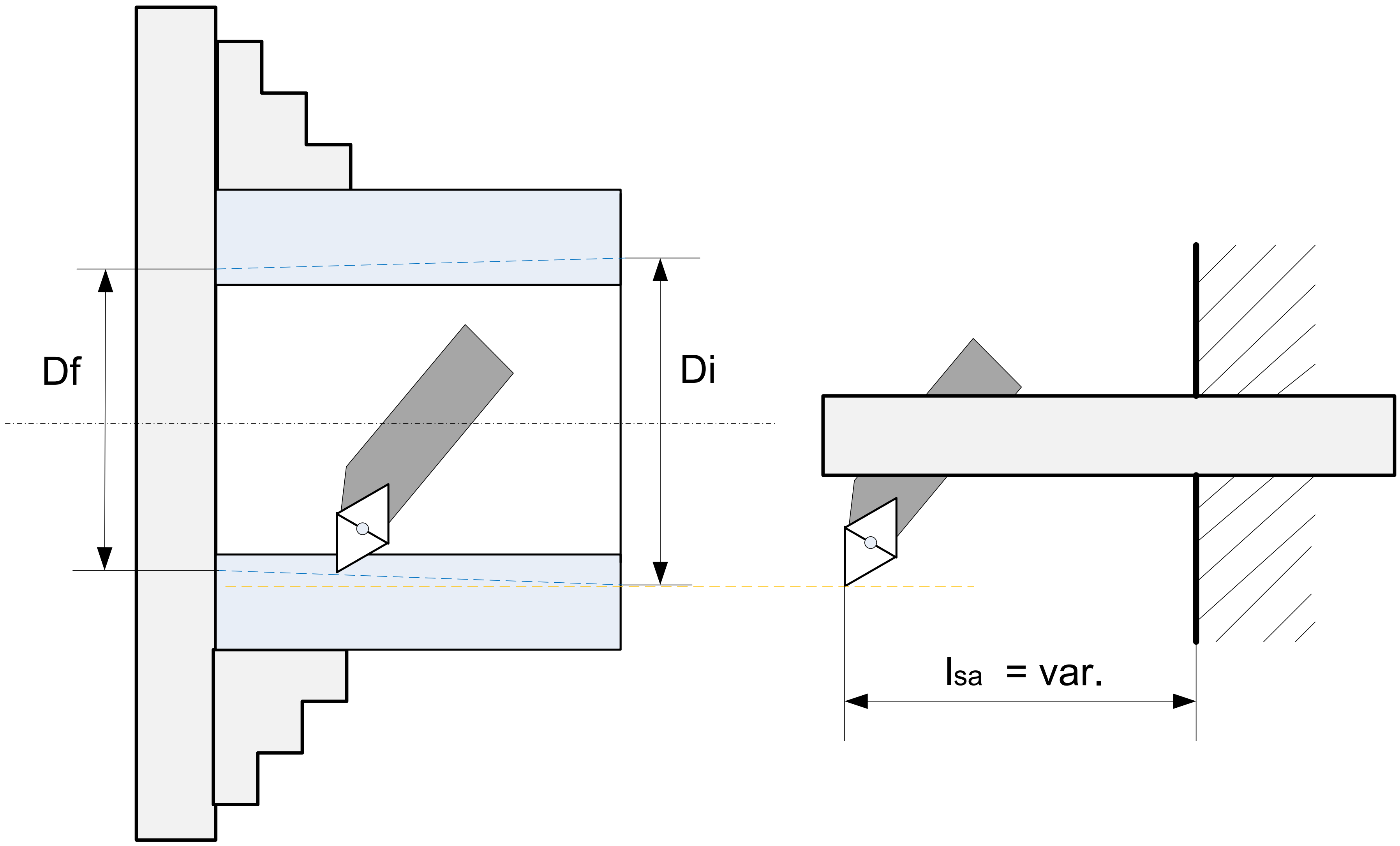


Fig. 18. Variation of errors due to tool deformation when machining bores with boring bar [1]

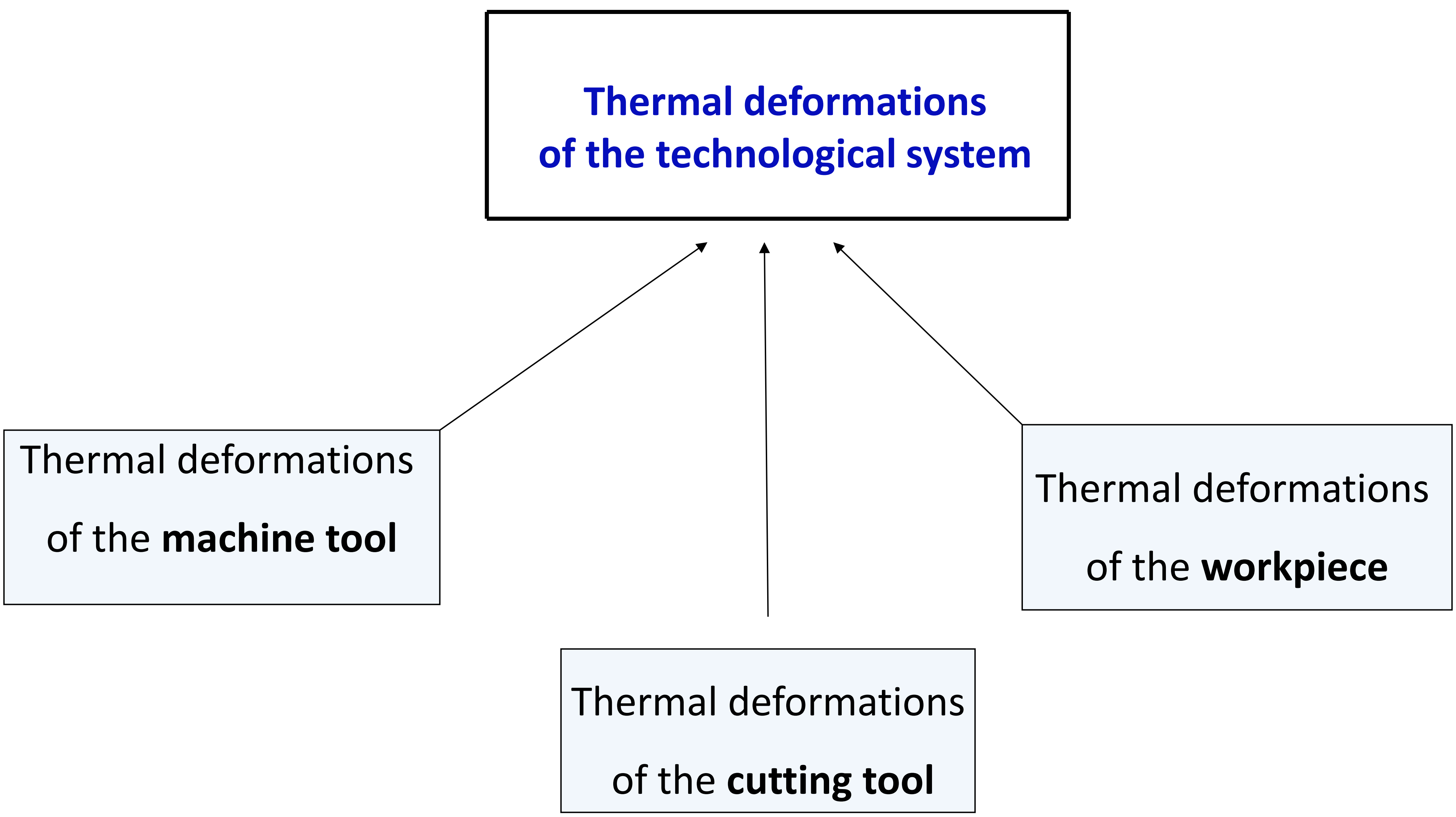
$$\varepsilon_{Di} = 2 \cdot y_i = \frac{2 \cdot Fr \cdot l_{\min}^3}{3 \cdot E \cdot I} \quad [mm] \tag{76}$$

$$\varepsilon_{Df} = 2 \cdot y_f = \frac{2 \cdot Fr \cdot l_{\max}^3}{3 \cdot E \cdot I} \quad [mm] \tag{77}$$

3.10 Thermal deformations of the technological system

Thermal deformations of technological systems refer to the dimensional changes and distortions in machine components and structures due to temperature variations. These deformations play a significant role in the performance, accuracy, and reliability of mechanical systems, especially in precision-dependent industries like manufacturing and aerospace.

Thermal deformations of the technological system are composed of the thermal deformations of the machine tool, the workpiece, and the cutting tool.



3.10.1 Thermal deformation of machine tools

Thermal deformations in machine tools are a critical concern in mechanical engineering, as they directly influence the accuracy, efficiency, and reliability of machining processes. Machine tools operate in environments where heat generation is inevitable due to friction, cutting forces, and internal components such as motors and spindles. These thermal effects lead to dimensional changes in the machine structure, which can compromise the precision of the machining process.

Sources of thermal deformations in machine tools

1.Internal heat generation:

1. Motors, spindles, and drives generate heat during operation, causing localized temperature increases.
2. Friction between moving components, such as bearings, guideways, and screws, contributes to uneven heating.

2.External factors:

1. Changes in ambient temperature, sunlight exposure, or proximity to heat sources can cause non-uniform expansion.
2. Prolonged operation without cooling mechanisms exacerbates temperature gradients.

3.Cutting process heat:

1. Heat from the cutting process is transferred to both the machine tool and the workpiece, leading to further deformation.

The thermal deformations occurring in the process can influence machining accuracy:

$$\Delta l = l_0 \cdot \alpha \cdot \Delta t \qquad [\mathrm{m}] \qquad (78)$$

Were,

Δl (Change in length):

•This represents the amount by which a material's length changes due to a temperature variation.

•It can be either positive (expansion) or negative (contraction), depending on whether the temperature increases or decreases.

l_0 (Initial length):

•The original length of the material before the temperature change.

•The longer the initial length, the greater the absolute deformation under the same conditions.

α (Coefficient of thermal expansion):

•This material-specific constant indicates how much the material expands per unit length for each degree of temperature change (commonly expressed in 1/°C or 1/K).

•Materials with a higher **α** (e.g., aluminum) expand more significantly compared to those with a lower **α** (e.g., steel or ceramics).

Δt (Change in temperature):

•The difference between the initial and final temperatures of the material.

•Greater temperature changes result in larger thermal deformations.

Volumetric thermal expansion occurs because the material's particles move more vigorously as the temperature increases, causing them to push farther apart, leading to an increase in volume.

$$\Delta V = V_0 \cdot \gamma \cdot \Delta t \quad [\mathrm{m}] \qquad (79)$$

The equation describes the volumetric thermal expansion of a material, were,

ΔV (Change in volume):

•This represents the change in the volume of a material due to a temperature variation.

•Similar to linear expansion, the volume change can be either positive (expansion) or negative (contraction), depending on whether the temperature increases or decreases.

V_0 (Initial volume):

•The initial volume of the material before any temperature change occurs.

•Just as with length, the larger the initial volume, the greater the absolute change in volume for the same temperature change.

β (Coefficient of volumetric expansion):

•This is the material's specific coefficient for volumetric expansion, often referred to as **beta**.

•The coefficient **β** is typically three times the coefficient of linear expansion (α) for isotropic materials. Therefore, **β ≈ 3α** for most materials.

•**β** quantifies how much the material's volume changes per unit of volume for each degree of temperature change. It has units of 1/°C or 1/K.

In turning operations, thermal deformations can significantly affect the quality and accuracy of the machined part. Turning is a machining process where a cutting tool removes material from a rotating workpiece. As heat is generated during cutting, various thermal deformations can occur that influence the precision of the operation.

For example:

If a cylindrical metal rod is heated, it will expand both in length and in diameter. The difference in diameter between the original and final dimensions would be described by the equation $\epsilon_d = d_1 - d_2 = 2 \cdot \Delta_{l_0}$, where Δ_{l_0} is the linear thermal expansion of the rod's length due to temperature increase.

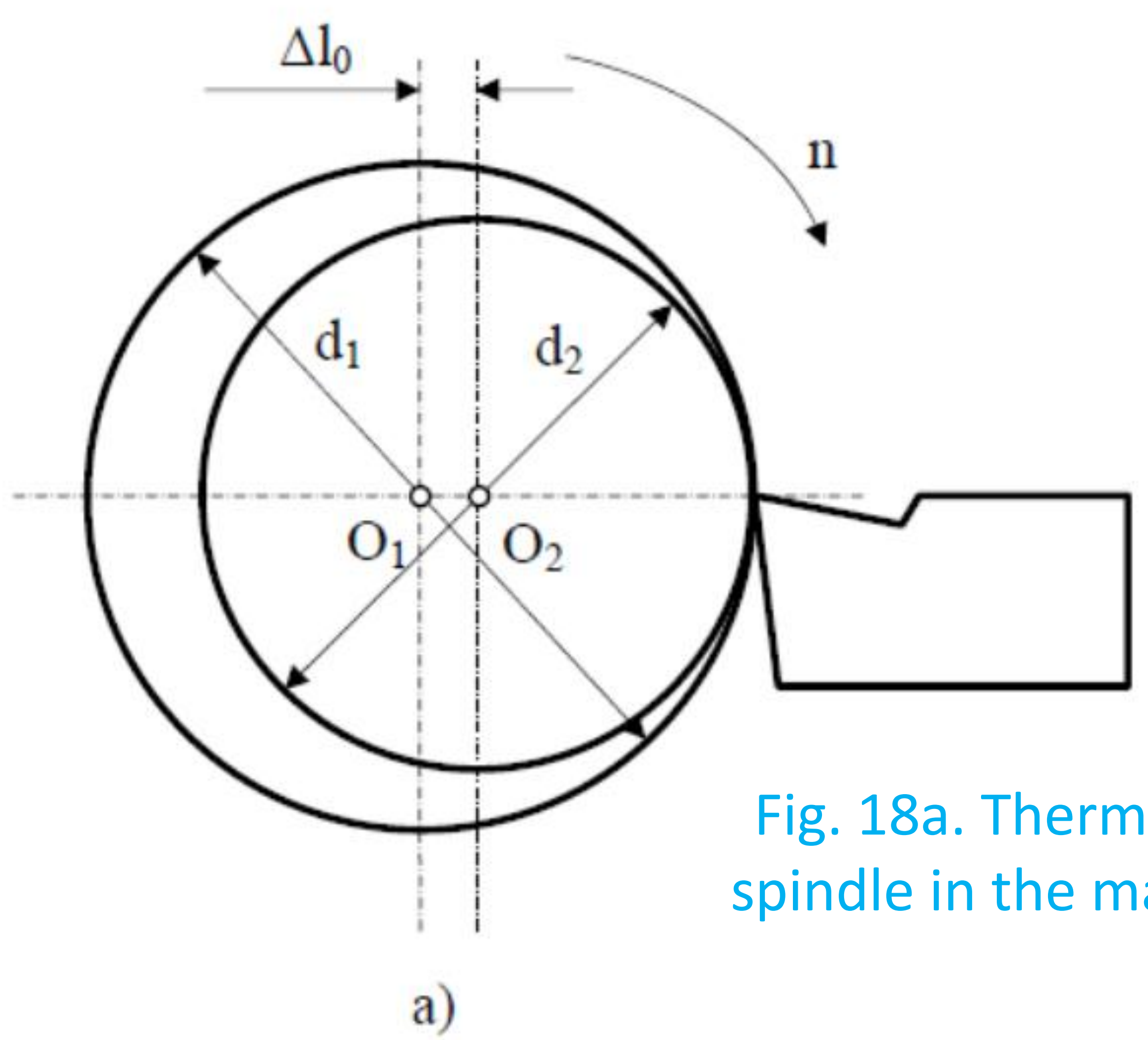


Fig. 18a. Thermal deformations of the main spindle in the machine unit – turning case [5]

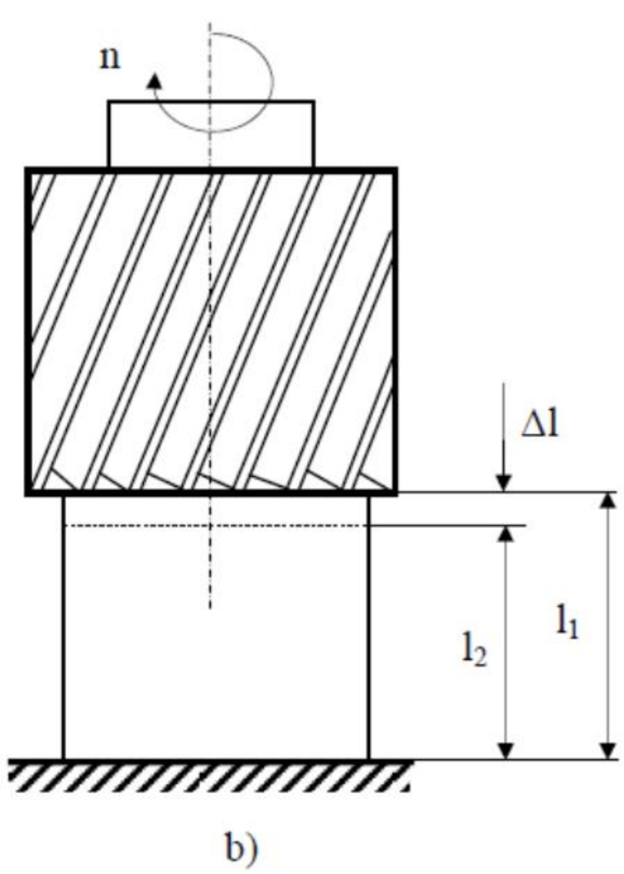
Calculation Example:

Let's assume a cylindrical metal shaft has an initial diameter $\boldsymbol{d_1}$ of 100 mm. When the temperature increases by 50°C, the metal expands and the length of the shaft changes by 0.2 mm (Δ_{l_0} = 0.2 mm). The equation suggests that the change in diameter $\boldsymbol{\epsilon_d}$ will be twice the thermal elongation in the length direction, so:

$$\varepsilon_d = 2 \cdot \Delta_{l_0} = 2 \cdot 0.2mm = 0.4mm$$

Thus, the difference in diameter between the initial and final dimensions would be 0.4 mm.

In milling operations, heat is generated at the cutting zone due to friction between the tool and the workpiece. This heat can cause both the tool and workpiece to expand. The change in dimensions, typically a length change, affects the machining accuracy and can lead to errors in part dimensions, such as undesired expansions or contractions of the workpiece.



The equation $\boldsymbol{\varepsilon_d}$ **= l_1 - l_2 = Δl** represents the thermal deformation of a component (typically the workpiece or tool) during the milling process.

Fig. 18b. Thermal deformations of the main spindle in the machine unit – milling case [5]

Calculation Example:

Suppose a milling machine processes a steel workpiece, and the initial length (**l_1**) is 100 mm. After the milling process, due to the heat generated, the length of the workpiece increases by 0.2 mm (Δl = 0.2 mm). The final length (**l_2**) will be:

$$l_2 = l_1 + \Delta_l = 100mm + 0.2mm = 100.2mm$$

Thus, the change in length (**Δl**) due to thermal deformation is **0.2 mm**, and the equation **$\varepsilon_d = l_1 - l_2 = \Delta l$** indicates that the part has expanded by that amount due to the thermal effects during milling.

Thermal deformation during milling is a crucial consideration in precision machining, especially in high-speed milling operations, where significant amounts of heat can be generated. We must account for these deformations to ensure that parts meet the required dimensional tolerances. By managing the temperature through cooling systems or adjusting process parameters, the effects of thermal deformation can be minimized, improving machining accuracy and surface finish.

3.10.2 Thermal deformations of the cutting tool

Thermal deformations of the cutting tool in machining processes, such as turning, milling, or drilling, are critical to understanding the overall precision and performance of the machining operation. During these processes, heat is generated at the cutting interface between the tool and the workpiece due to friction, deformation of the material, and other factors. This heat affects the tool's geometry, leading to thermal deformations, which can impact the accuracy, tool life, and surface finish of the machined part.

Causes of thermal deformations in the cutting tool

Heat generation at the cutting edge:

The primary source of thermal deformations in the cutting tool is the heat generated at the cutting edge. As the tool engages with the workpiece, the high cutting forces cause localized heating. This heat is then transferred to the cutting tool, resulting in temperature increases along the tool’s cutting edge and body.

The heat is a combination of friction between the tool and workpiece, as well as the energy required to deform the material being cut.

Heat distribution and tool material properties:

The thermal deformations in the tool are not uniform, as the heat distribution varies across the tool. For instance, the cutting-edge experiences higher temperatures compared to the shank or body of the tool.

The material of the cutting tool plays a significant role in its ability to withstand heat. High-performance materials like carbide, ceramic, or cubic boron nitride (CBN) are designed to resist thermal deformation and maintain tool integrity under high-temperature conditions.

Cutting conditions:

The amount of heat generated depends on several factors, including cutting speed, feed rate, depth of cut, and the material properties of both the tool and the workpiece.

High cutting speeds, deeper cuts, and larger feed rates generally lead to more heat generation, which exacerbates thermal deformations in the tool.

Effects of thermal deformations on machining performance

Dimensional accuracy:

The thermal deformations of the cutting tool can directly impact the dimensional accuracy of the part being machined. For example, if the cutting edge of the tool expands, it may cut deeper than intended, leading to overcutting or undercutting of the workpiece.

Surface finish:

Changes in the cutting geometry due to thermal deformations can result in poor surface finish. A tool that has warped or undergone thermal distortion may generate rougher surfaces or an uneven cut, leading to the need for additional finishing operations.

Tool life:

Thermal deformations contribute to the wear and eventual failure of the tool. The constant expansion and contraction can cause microfractures in the material, reducing the tool’s overall life.

If the tool loses its sharpness or cutting efficiency due to thermal effects, it will require frequent replacement, leading to increased costs and downtime in the machining process.

Cutting forces and vibration:

Thermal deformations may alter the cutting forces applied during the operation. This can lead to vibrations, chatter, or instability in the machining process. The cutting forces may also become uneven, leading to inconsistent cutting and possible damage to both the tool and the workpiece.

In the case of turning the average value of the temperature released in the chipping process can be determined with the relation:

$$T \cong v^{a} \cdot f^{b} \qquad (80)$$

Were,

T - represents the temperature of the system, such as the cutting zone in a machining operation (like turning, milling, or drilling).

v - the cutting speed refers to the speed at which the cutting tool moves relative to the workpiece. It typically affects the amount of heat generated during machining, as higher cutting speeds usually result in more heat due to increased friction and deformation.

f - while feed rate refers to how fast the cutting tool advances through the material in one revolution (in turning) or along its path (in milling).

a *and* b - these are empirical constants that are determined based on experimental data or modeling. They describe how temperature changes with variations in cutting speed and depth/feed rate. The values of a and b depend on the material being machined, the tool material, and the specific conditions of the machining process.

Interpreting the equation:

Cutting Speed (v) and Temperature (T):

The term $\boldsymbol{v^a}$ suggests that the temperature is related to the cutting speed raised to the power of a. This implies that as cutting speed increases, the temperature increases, but at a rate depending on the value of a.

In many cases, the relationship between cutting speed and temperature can be nonlinear, so the exponent a helps quantify this effect. Typically, higher cutting speeds lead to greater temperature rise due to increased heat generation.

Cutting depth or feed rate (f) and Temperature (T):

The term $\boldsymbol{f^b}$ suggests that temperature also depends on the cutting depth or feed rate raised to the power of b. Larger cutting depths or feed rates generally lead to more heat generation, as the tool engages with more material.

Like cutting speed, the effect of cutting depth/feed rate on temperature may not be linear, and the value of b determines how significant this effect is. In general, higher values of b would indicate a more significant impact of cutting depth or feed rate on temperature.

- The cutting speed influences the temperature. Increasing the cutting speed reduces the time available for heat dissipation, which in turn leads to a temperature increase.
- A significant portion of the heat generated is absorbed by the chip. The heat distribution among the chip, blank, and tool depends on the processing parameters and the conditions under which chip occurs.
- Although the percentage of heat absorbed by the cutting tool is relatively small compared to the heat absorbed by the blank and the chips, its significance becomes evident due to the tool's much smaller mass in relation to that of the blank.

Tab.1. Thermal distribution in turning and drilling processes [5]

Operation	Chips [%]	Workpiece [%]	Cutting tool [%]
Turning (v=100m/min)	75	20	4 - 4,5
Drilling	25	54	20

The variation of thermal deformation of the cutting tool is influenced by multiple factors, including heat generation, heat distribution, and thermal conductivity of the tool material. During the cutting process, a significant amount of heat is generated at the contact zone due to friction and plastic deformation.

This heat is partially absorbed by the tool, the blank, and the chips, with the tool being particularly vulnerable due to its smaller mass relative to the other components.

As the heat accumulates, the temperature of the cutting tool increases, leading to thermal expansion and deformation. The degree of thermal deformation depends on:

1.Cutting speed: Higher speeds reduce heat dissipation time, increasing tool temperature and, consequently, deformation.

2.Material properties: Tools with low thermal conductivity and high thermal expansion coefficients deform more significantly under the same thermal conditions.

1.Tool geometry: Thin or slender tools are more prone to thermal deformation compared to bulkier tools.

2.Heat dissipation efficiency: The cooling system or ambient conditions influence the extent to which heat is removed from the tool.

The resulting thermal deformation can alter the tool geometry, impacting dimensional accuracy, surface finish, and the overall efficiency of the machining process. For precision machining, understanding and controlling this variation is critical to minimize errors and ensure tool longevity.

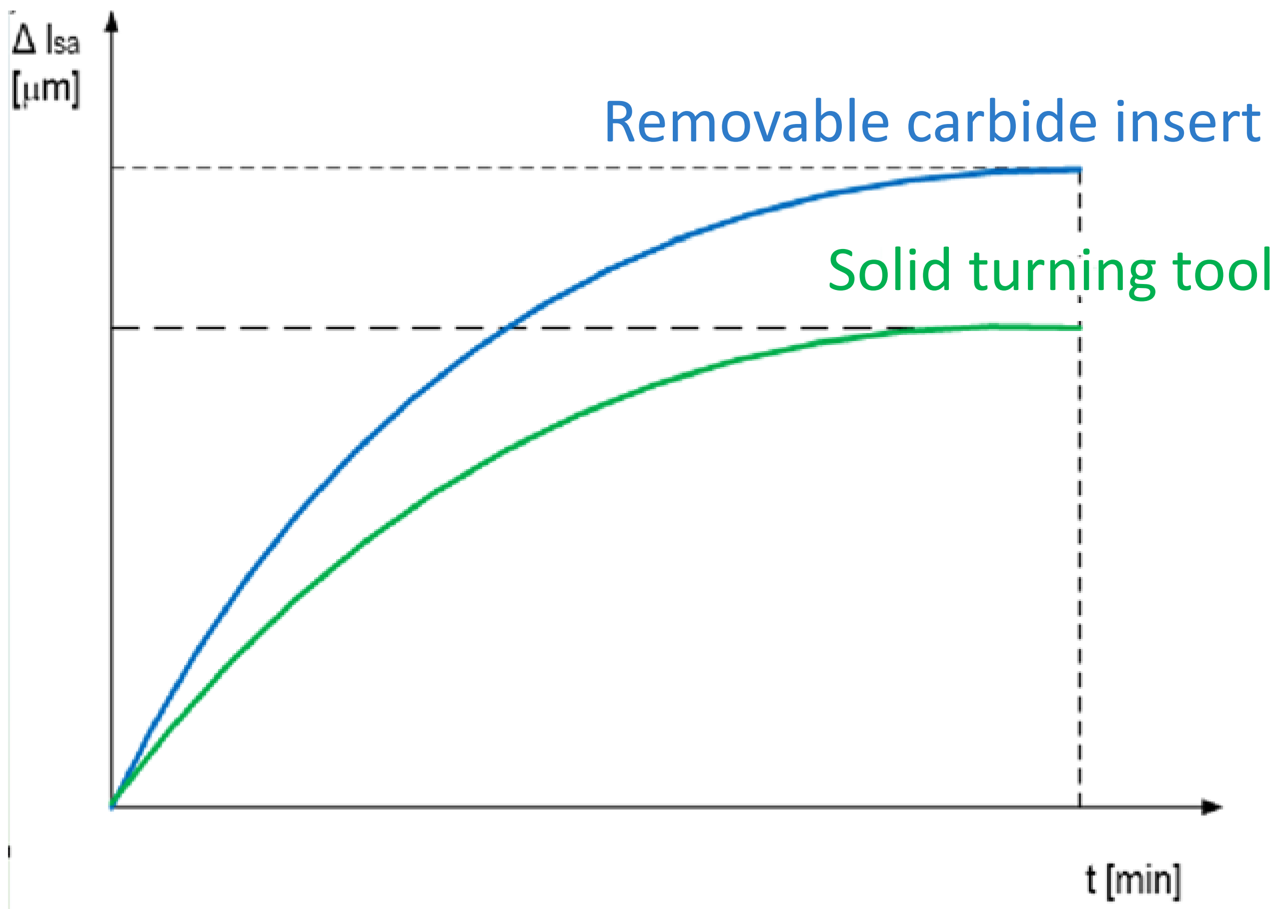


Fig. 19. Variation of thermal deformation of the cutting tool [1]

The higher thermal deformation in removable inserts is primarily caused by heat being concentrated in the small mass of the insert, as opposed to being distributed over the larger mass of a one-piece tool. Additionally, the heat transfer from the insert to the tool body is inefficient, resulting in further accumulation of heat within the insert.

3.10.3 Thermal deformations of the workpiece

Thermal deformations refer to changes in the shape, size, or geometry of a blank caused by temperature variations. A *workpiece* - a raw piece of material (metal, plastic, or composite) - is subjected to heating or cooling during manufacturing processes. This thermal exposure results in material expansion or contraction, leading to deformations. Understanding and controlling these deformations is crucial to ensure product quality and dimensional accuracy.

The parameters influencing the thermal deformations of the blank include the following:

•**Cutting parameters**: feed rate, cutting speed, and depth of cut;

•**Properties of the workpiece**;

•**Thermal expansion coefficients**: both linear and volumetric;

•**Tensile strength** of the blank material.

Thermal deformation of the blank has a significant impact on dimensional accuracy, particularly in situations where small or low-mass blanks are involved, or during precision finishing operations. This effect is more pronounced due to the reduced thermal inertia of small blanks, which makes them more susceptible to temperature fluctuations.

In finishing operations, even minor thermal deformations can lead to deviations from specified tolerances, compromising the quality and functionality of the final product. Proper control of cutting parameters and cooling strategies is essential to minimize these effects and maintain the required dimensional accuracy.

During milling and plane grinding, uneven heat distribution across the cross-section of the blank leads to variable dimensional errors, which, in turn, negatively affect the shape accuracy of the machined surfaces. This non-uniform thermal behavior can cause localized expansion or contraction, resulting in warping, distortion, or deviations from specified tolerances. Proper thermal management, including optimized cutting parameters and cooling methods, is essential to mitigate these effects and maintain surface precision.

3.11 Measures to reduce errors due to thermal deformations

Thermal deformation in machining processes can significantly impact **dimensional accuracy** and **surface quality** of the final product. To minimize these effects, a variety of measures can be implemented to address heat generation, distribution, and dissipation during machining operations.

1. Optimized cutting parameters

Adjusting cutting parameters such as feed rate, cutting speed, and depth of cut is essential to reduce heat generation.

•**Lower cutting speeds**: Reducing the speed minimizes friction and heat buildup.

•**Controlled feed rate**: Ensuring a steady and moderate feed rate helps distribute cutting forces more evenly, reducing localized heating.

•**Shallow depth of cut**: Limiting the depth of cut prevents excessive energy concentration on a small surface area.

By balancing these parameters, heat generation can be controlled to a level that minimizes thermal deformation.

2. Efficient cooling and lubrication

Implementing effective cooling and lubrication methods is critical for managing heat during machining.

•**Cutting fluids**: The use of coolants helps dissipate heat rapidly, protecting both the blank and cutting tool.

•**Flood cooling**: Provides uniform cooling across the entire machining zone, reducing temperature gradients.

•**Mist and cryogenic cooling**: Advanced cooling systems such as mist lubrication or liquid nitrogen can effectively manage heat without excessive fluid consumption.

•**Air cooling**: For materials sensitive to thermal shock, air cooling offers a non-intrusive solution to lower temperature levels.

Proper cooling prevents localized heating and ensures even heat distribution across the blank.

In the context of thermal deformation during machining, **fixtures are generally considered small enough relative to the workpiece to be neglected in the calculation of the total processing error**. This is because the primary source of thermal deformation comes from the workpiece itself, which has a much larger mass and is subject to greater heat exposure during the machining process.

Fixtures, while important for holding the workpiece in place, do not typically undergo the same level of thermal stress as the workpiece. Consequently, their thermal expansion is usually minimal and does not significantly affect the overall dimensional accuracy of the machined part. In most cases, the thermal deformation of the blank and cutting tool are the major contributors to processing errors, with the fixture's influence being relatively small in comparison.

However, if fixtures are not designed with thermal stability in mind (e.g., if they are made from materials that expand significantly under heat), there could be localized effects that need to be considered. But generally, fixtures are designed to have minimal thermal impact, and any potential errors introduced by them are often considered negligible in the broader context of thermal deformation analysis.

Wear of elements in the technological system, especially those involving relative motion between components, plays a significant role in the overall performance and machining accuracy.

Component wear occurs due to the continuous friction and relative motion between different machine elements in contact during operation. Over time, this friction leads to the gradual loss of material, which results in changes to the original geometry and surface integrity of the components involved. As the wear progresses, the precision of the components diminishes, causing inaccuracies in the machining process.

One of the most critical elements in the technological system that can influence machining accuracy is the **wear of the machine unit guides**. The guides, which help maintain the correct positioning and movement of machine tools, are essential for ensuring that the cutting tool follows the intended path with high precision. As these guides wear down over time, they can lead to increased play or misalignment in the movement of the machine, causing deviations from the desired path. This, in turn, affects the dimensional and shape accuracy of the machined part.

When the guides wear, the movement of the machine tool becomes less precise, which can result in poor surface finishes, incorrect dimensions, and reduced overall part quality.

The wear of other critical components, such as spindles, bearings, or linear guides, can also contribute to errors in the machining process, amplifying inaccuracies and reducing the lifespan of the equipment.

To mitigate these issues, regular maintenance, monitoring of wear patterns, and timely replacement or repair of worn components are necessary. Additionally, improving the design of the guides, using materials with higher wear resistance, and optimizing lubrication can help reduce wear and ensure the continued accuracy and longevity of the technological system.

3.12 Influence of technological system vibrations on machining accuracy

The influence of vibrations of a technical system on machining accuracy is a critical consideration in manufacturing and machining processes. Vibrations can arise from various sources within the machining system, including the cutting tool, workpiece, machine components, or external environmental factors. These vibrations can adversely affect the quality, precision, and efficiency of machining operations.

The vibratory motion in machining systems can be characterized by the following key aspects:

•**High-frequency oscillatory motion**: This refers to rapid, repetitive movements within the system that occur during machining.

•**Amplitude relation**: The amplitude of the vibration, or the distance between the tool edge and the machining surface, tends to increase simultaneously with the cutting speed (the speed at which material is removed).

Consequences of vibratory motion:

1. Decrease in dimensional accuracy: Vibrations can cause deviations in the final dimensions of the workpiece, leading to reduced precision.

2. Decrease in surface quality: The machined surface may have irregularities or roughness due to unstable tool motion.

3. Wear or breakage of the cutting tool: Vibrations increase stress on the tool, accelerating wear and potentially causing breakage.

4. Failure of certain machine components: Prolonged exposure to vibratory forces can lead to mechanical fatigue or failure of parts within the machine unit.

3.13. Causes of vibration in the technological system

Vibrations in technological systems arise due to a variety of reasons, ranging from design flaws to external influences. Understanding these causes is crucial for identifying and mitigating their effects on machining accuracy, tool life, and product quality.

External sources of vibrations in machining systems

External vibrations significantly impact machining processes by introducing instability, reducing accuracy, and affecting surface quality. Below are the key sources external to the machining process:

1. Vibrations transmitted through the foundation

Vibrations from nearby machinery or equipment are transmitted through the foundation to the machining system. For example, heavy presses, compressors, or vehicles can cause disturbances.

•**Impact**: These vibrations interfere with the precision of the machining process, leading to dimensional errors or surface defects.

•**Prevention**:

- Use vibration-isolating mounts or pads for the machine.
- Improve the foundation's rigidity and stability.
- Maintain adequate distance between machinery to reduce interference.

2. Vibrations caused by unbalanced masses in rotational motion

Rotating components, such as spindles, motors, or tools, can become unbalanced due to uneven mass distribution. This imbalance creates centrifugal forces that cause vibrations.

Impact: Unbalanced rotational motion leads to irregular tool movements, causing chatter, tool wear, and surface irregularities.

•**Prevention**:

- Ensure proper balancing of rotating components.
- Regularly inspect and align spindles and motors.
- Use high-quality, balanced tool holders.

3. Vibrations produced by various shocks

Shocks occur due to sudden impacts, such as collisions between machine parts, tool changes, or external forces like dropping objects near the machine.

•**Impact**: Shocks create transient vibrations that disrupt the machining process and may damage sensitive components.

•**Prevention**:

- Avoid sudden changes in machine operation.
- Install shock absorbers or dampers on machines prone to impacts.
- Train operators to handle tools and materials carefully.

Internal sources of vibrations in the technological system

Internal vibrations are generated directly during the machining process. They arise from imperfections in the system or the dynamic interaction between the tool, workpiece, and material being processed. Below are the primary internal sources:

1. Non-uniformity of processing layer and material structure

Uneven distribution of material to be removed or variations in the material's structure can create forces that cause vibrations.

•**Impact**: Leads to irregular tool engagement, affecting dimensional accuracy and surface quality.

•**Prevention**:

- Ensure consistent raw material quality.
- Use appropriate machining strategies to handle variations in material properties.

2. Radial runouts of the mandrel toolholder

Misalignment or imbalance in the spindle causes radial deviations, leading to vibrations.

•**Impact**: Results in uneven cuts, chatter, and accelerated tool wear.

•**Prevention**:

- Regularly align and balance the spindle.
- Use high-precision tool holders and fixtures.

3. Uneven penetration of the cutting tool's edges into the material

If the cutting tool's edges do not engage the material uniformly, it generates variable cutting forces and vibrations.

•**Impact**: Produces inconsistent chip formation, reduces surface quality, and increases tool wear.

•**Prevention**:

- Maintain sharp and uniform cutting edges.
- Optimize cutting parameters like feed rate and depth of cut.

4. Internal phenomena of the cutting process

The process of chip formation and discharge can introduce vibrations due to interruptions or dynamic forces during material removal.

•**Impact**: Disrupts the machining process, affecting the stability of the system and the quality of the finished surface.

•**Prevention:**

- Optimize the cutting process to facilitate smooth chip flow.
- Use proper coolant or lubrication to reduce friction and chip adhesion.

3.14 Types of vibrations in machining system

1. Forced vibrations

Forced vibrations occur when periodic forces continuously act on the technological system, causing it to vibrate at a specific frequency determined by the external force.

Causes:

- Gearboxes or feed mechanisms transmitting irregular forces.
- Unbalanced rotating elements within the system.
- Electric motor-induced vibrations.
- Variable cutting forces, such as during milling or turning operations with inconsistent material removal rates.

These vibrations are directly linked to the characteristics of the external force and can often be minimized by addressing the source of the periodic disturbances.

1. Forced vibrations

$$\left.\begin{array}{l} F_{el} + F_{am} = 0 \\ F_{el} = \frac{1}{W} \cdot y \\ F_{am} = C \cdot \frac{dy}{dt} \end{array}\right\} \quad \begin{array}{ll} m \cdot \frac{d^2 y}{d^2 t} + C \cdot \frac{dy}{dt} + \frac{1}{W} \cdot y = 0 & (81) \\ m \cdot \frac{d^2 y}{d^2 t} + \frac{1}{W} \cdot y = 0 & (82) \end{array}$$

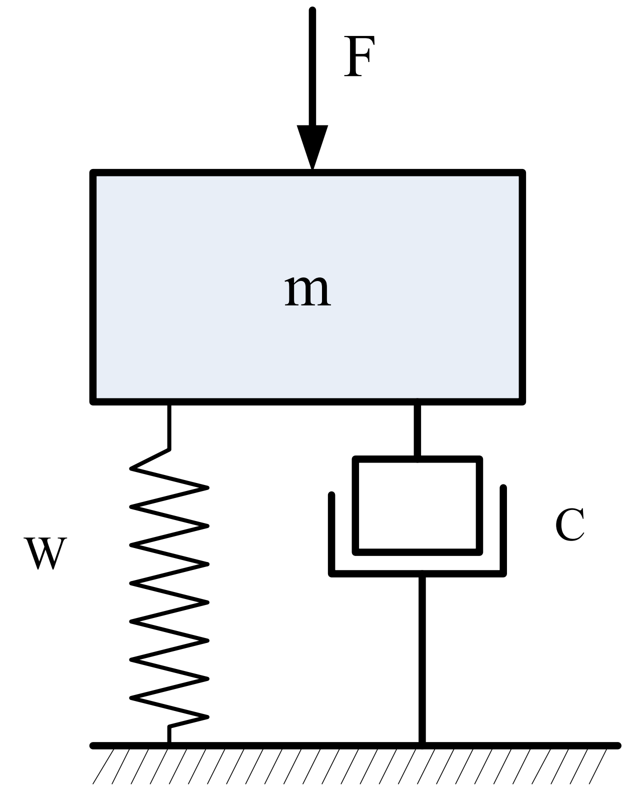


Fig. 20. Simplified technological system [2]

$$y = A \cdot \cos \omega t + B \cdot \sin \omega t$$

$$y = B \cdot \sin \omega t$$

$$f = \frac{\omega}{2 \cdot \pi} = \frac{1}{2 \cdot \pi} \cdot \sqrt{\frac{1}{W \cdot m}} \qquad (83)$$

$F_{el} + F_{am} = 0$ The sum of the two forces equal 0, representing a balance of forces.

$F_{el} = \frac{1}{W} \cdot y$ The elastic force is the **restoring force** that is proportional to displacement y.

$F_{am} = C \cdot \frac{dy}{dt}$ The **force from the damper** is the damping force, proportional to velocity.

Equation of Motion:

$$m \frac{d^2 y}{dt^2} + C \frac{dy}{dt} + \frac{1}{W} y = 0 \qquad (84)$$

This is damped free vibration equation, where:

- *m* – is the mass [kg]
- *C* – is the damping coefficient [kg/s]
- *W* – is related to the system stiffness [s^2/kg]

If damping is neglected (C=0), the equation simplifies to:

$m\frac{d^2y}{dt^2} + \frac{1}{W}y=0$ (85) - undamped free vibrations.

Solutions for Undamped Vibrations – the general solutions

$y = A \cdot \cos(\omega t) + B \cdot sin\ (\omega t)$, where A and B are constants determined by initial conditions.

If only sine term remains, we get:

$$y = B \cdot \sin(\omega t) \qquad (86)$$

The frequency of oscilation is given by:

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{1}{Wm}} \qquad (87)$$

This indicates that the system's frequency depends on the mass *m* and stiffness parameter *W*.

2. Self-vibration, or self-excited vibration, occurs in a technological system when an inherent instability or energy feedback leads to sustained oscillations, even if the system is initially at rest. These vibrations arise due to a non-linear interaction between components of the system, such as friction, fluid-structure interactions, or other dynamic forces.

Key characteristics of self-vibration include:

- High Amplitude: The oscillations can grow in amplitude as the system reaches an unstable equilibrium. This is often due to the energy fed back into the system from its internal dynamics.
- Low Frequency: These vibrations typically occur at lower frequencies because they are related to the natural frequencies of the system and are often influenced by factors like mass, stiffness, and damping.

Self-excited vibrations are oscillations that arise and sustain themselves due to the internal energy of a system, rather than an external periodic force. These vibrations occur when a system's feedback mechanisms amplify small disturbances, leading to sustained or growing oscillations.

In machining processes, self-excited vibrations typically result from dynamic interactions between the cutting tool and the workpiece, such as variations in cutting forces, chip formation stages, or frictional effects. Unlike forced vibrations, which cease when the external force is removed, self-excited vibrations persist due to internal energy sources within the system.

Several theoretical models explain the origins of self-excited vibrations in machining:

Taylor's Hypothesis:

1. Vibrations arise due to fluctuations in the **cutting force** during the four stages of chip formation:
   a. Elastic deformation
   b. Plastic deformation
   c. Necking
   d. Breaking
2. These force variations introduce periodic disturbances, causing oscillations.

Kashirin's Theory:

1. Vibrations result from variations in **friction forces** on the tool's clearance face.
2. Changes in contact conditions between the tool and workpiece lead to unstable oscillations.

Sokolovsky's theory explains self-excited vibrations in machining by attributing them to the continuous variation of **effective geometrical parameters** as the cutting tool interacts with surface irregularities.

Key Points of Sokolovsky's Theory

•As the tool moves across the workpiece, the cutting-edge encounters **variations in surface geometry**, which cause fluctuations in cutting forces.

•These fluctuations alter the tool’s effective cutting parameters (e.g., rake angle, clearance angle), leading to **instabilities** in the cutting process.

•This dynamic interaction between tool and workpiece can sustain or amplify vibrations, resulting in **chatter**.

Harnis and Grig’s theory explains self-excited vibrations in machining as a result of the continuous variation of chipping depth caused by the interaction between:

1.Irregularities from previous machining (surface roughness left by the tool).

2.Oscillations of the current machining process, which further modify the depth of cut.

Key Mechanism:

•As the cutting tool moves, it engages with surface irregularities from the previous machining pass.

•This alters the depth of cut dynamically, leading to variations in the cutting force.

•The fluctuating force feeds back into the system, sustaining or amplifying vibrations, creating a self-exciting effect (chatter).

Tobias' theory explains self-excited vibrations in machining as a result of the **variation in cutting forces** that occurs at two critical moments:

a. When the cutting tool enters the unformed material.

b. When the tool is rejected by the roughened surface left by previous passes.

Key Mechanism:

•As the tool engages with the workpiece, the cutting force increases due to **material resistance**.

•The tool's oscillatory motion, combined with the surface irregularities left from previous machining passes, causes **periodic variations in the cutting force**.

•This force variation **induces a feedback loop**, where the tool's movement reinforces vibrations instead of dampening them.

3. Vibrations stress relief are a type of vibration that occurs in technological systems when periodic forces (such as shocks or brief impacts) are applied to the system, causing it to vibrate at its own natural frequency even after the external force has ceased. These vibrations are known for their persistence after the triggering force has stopped working, as the system continues to oscillate independently.

When heat treatment is not practical or economically feasible due to impracticality or unfeasibility, it offers an alternative to traditional thermal stress-relief techniques.

The structure's natural modes of vibration may be excited when periodic external forces, such as mechanical shocks or short impulses, are applied to a system. The resonance modes of the structure are corresponded to by applying vibrations at specific amplitudes and frequencies.

The duration of the treatment is dependent on the geometry and material and can be between several minutes and over an hour.

Key characteristics of vibrations self relief include:

1.Triggering by short-duration forces: These vibrations are typically initiated by brief, periodic forces or shocks applied to the system. For example, a sudden impact or a force applied for a short duration can set the system into vibration.

2.Continuation after force ceases: After the external force is removed, the system continues to vibrate at its natural or resonant frequency, meaning the system's inherent dynamics (such as its mass and stiffness) dictate the frequency of the vibration.

3.Low rigidity systems: These vibrations are more prominent in systems with low rigidity, such as tools used in machining processes (turning, grinding, planing, etc.). In such systems, the lack of stiffness allows for the amplification of oscillations, making the system more prone to self-excitation and continued vibration.

4.Natural frequency of the system: The system's natural frequency is key in these vibrations. When a shock or force is applied, it can excite the system to oscillate at its resonant frequency, leading to vibrations that persist even after the force stops. These vibrations may decay slowly, depending on the damping characteristics of the system.

Examples of occurrence:

•**Planing** – the tool periodically engages and disengages with the workpiece, leading to cyclical force variations.

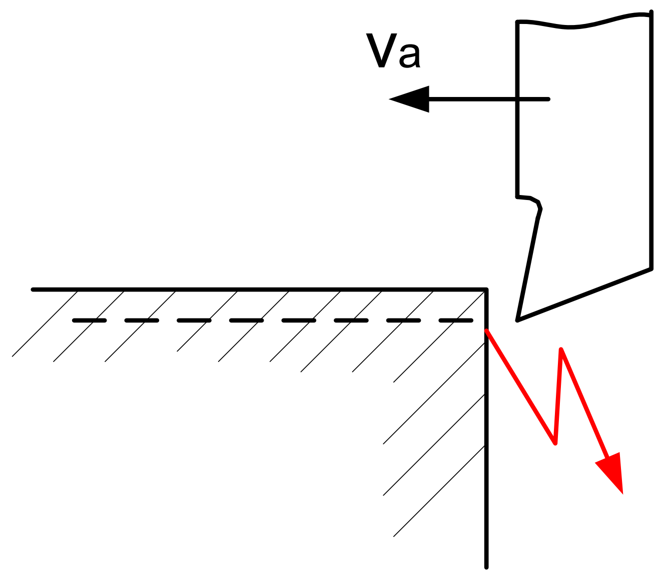


Fig. 21. Planing - Damped forced vibration [2]

•**Shaping** – the chisel undergoes repeated impacts, causing fluctuations in cutting forces.

•**Internal turning** – the tool's interaction with the inner surface of a workpiece can cause periodic deflections and force variations.

•**Grinding (external and internal cylindrical surfaces)** – Abrasive grains alternately engage and disengage with the material, leading to pulsating forces and potential self-excited vibrations.

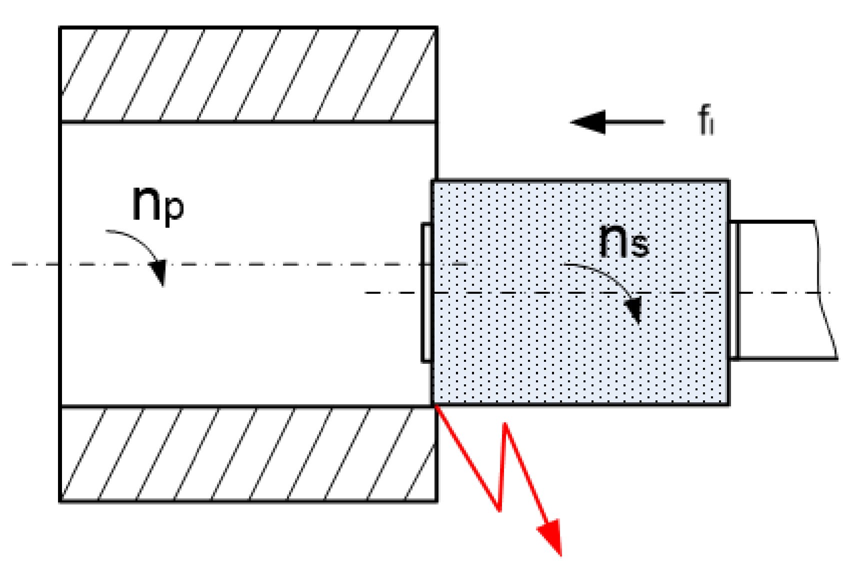


Fig. 22. Internal grinding - Damped forced vibration [2]

Utilization of positive γ rake angles

In some cases, incorporating small facets with negative γ clearance angles to optimize cutting performance and tool stability.

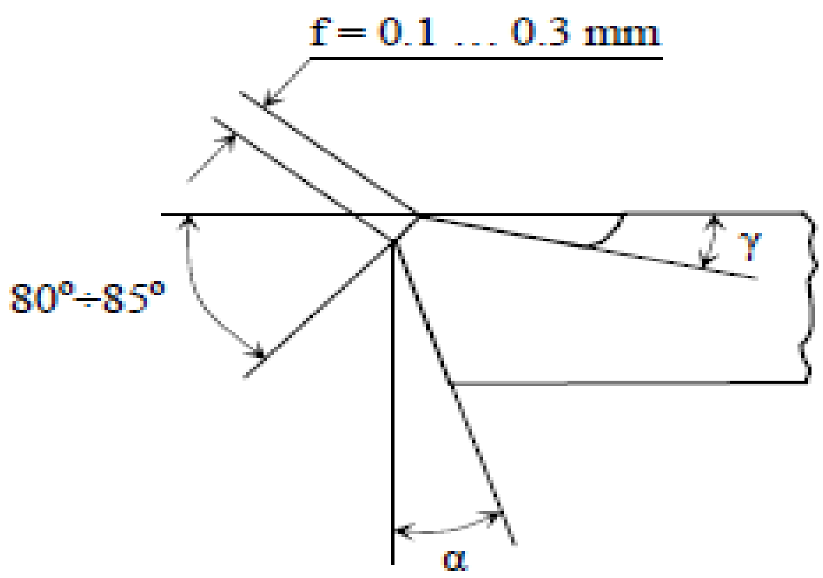


Fig. 23. Turning tool with negative rake angle [1]

Optimization of cutting tool geometry and positioning

•**Minimization of angle (α):** Selecting the smallest possible seating angle while avoiding excessive friction between the seating face and the workpiece.

•**Minimization of insert's corner radius:** Using the smallest feasible tip radius to enhance precision and reduce cutting forces.

•**Use of deployment of cutting tools:** Ensuring sharpness and efficiency by employing new or well-maintained tools.

•**Minimization of tool overhang length:** Keeping tool overhang as short as possible to improve rigidity and reduce vibrations.

•**Correct center alignment of the cutting tool:** Ensuring proper positioning for optimal cutting performance and reduced wear.

3.15 Measures to reduce the effects of vibration

1. **Enhancing the rigidity of technological system components**

   Including the elimination of play in joints, the use of additional bearings, the implementation of rigid portcullis supports, and the repair or reconditioning of sub-assemblies to ensure structural stability and precision.

2. **Implementation of additional elastic systems for vibration energy absorption**

   Including the use of vibration dampers to mitigate oscillations and enhance system stability.

3. **Processing using serrated (reversed) knives**

   Enhancing cutting efficiency and reducing material deformation through the use of reversed, serrated blades.

4. **Optimal selection of cutting parameters**

   *Including the use of low or very high cutting speeds, low chipping depths, and high feed rates to improve efficiency and reduce vibration.): **u***utilization of cutting tool edge angle.**

   Employing tools with ranging from 75° to 90° to enhance cutting performance and stability.

Utilization of back tools in planing

Back tools, when elastically deformed under cutting forces, follow a tangent path to the machined surface, preventing unwanted intersections that typically occur with straight-bodied knives. This improves surface quality and reduces cutting resistance.

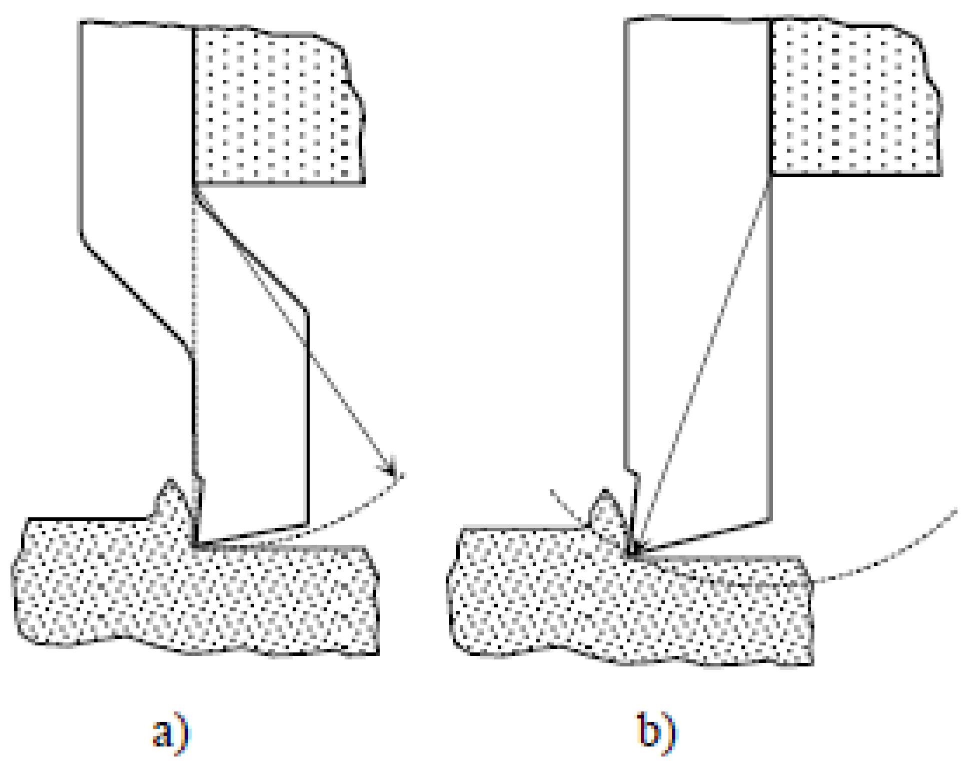


Fig. 24. Planing and shaping knives [5]

- Utilizing low or high cutting speeds to avoid the critical vibration zone, which varies with each tool-material pair;
- Using shallow cutting depths and high feed rates to produce short, thick chips;
- Utilizing vibration dampers to reduce tool chatter and improve stability.

3.16. Influence of internal stresses on machining accuracy

Causes:

1. Semi-finished product stage (structural stresses):

- During the semi-finished product stage, materials often have internal stresses from prior manufacturing processes like casting, forging, or extrusion. These processes can create uneven cooling rates or uneven plastic deformation, leading to residual stresses in the material.

2. Mechanical processing stage (technological stresses):

- In the mechanical processing stage, such as machining (milling, turning, grinding), stresses are induced by the cutting forces between the tool and the workpiece. These forces can create deformation in the material, especially at the tool-workpiece interface. The cutting depth, feed rate, and cutting speed all influence the magnitude and distribution of these stresses.

3. Heat treatment stage (thermal stresses):

- Heat treatment processes like quenching, annealing, or normalizing involve significant changes in temperature. During heating or rapid cooling, different parts of the material expand or contract at different rates, leading to thermal stresses. These stresses can be especially pronounced in materials with complex geometries.

Effect:

1. Dimensional Errors:

- Residual stresses can cause the final part to deviate from the intended dimensions. For example, a part might shrink or expand unpredictably as internal stresses are relieved or redistributed during machining or heat treatment.

2. Shape Errors:

- Shape errors refer to deviations from the desired geometric form of a part. These can occur when internal stresses cause warping or bending of the material. Such errors are common in parts with non-uniform shapes or after operations like quenching, where thermal stresses cause uneven material contraction.

3. Positional Errors:

- Positional errors refer to misalignment of features or surfaces relative to one another. These can occur if the internal stresses cause deformation of the part during processing. Misalignment can also happen if parts are deformed unevenly during heat treatment or machining, affecting how components fit together.

In manufacturing, internal stresses induced during various stages (like forming, machining, or heat treatment) can lead to dimensional, shape, and positional errors in finished parts.

These stresses cause distortions in the material that affect the final geometry of the part, influencing its performance and fit within an assembly. Understanding and controlling these stresses is crucial to ensuring high-quality, precise components in engineering applications.

3.16.1 Internal stresses in castings

Internal stresses in castings arise due to temperature gradients during cooling and the restriction of free shrinkage in different sections. Factors such as varying wall thicknesses, complex geometries, and missing connections contribute to stress accumulation.

In some cases, these internal stresses can become so significant that they lead to cracks, fissures, or even complete fracture. However, such stresses do not always manifest immediately after casting. Over time, they may cause gradual deformation of the part, impacting dimensional stability and mechanical performance.

3.16.2 Internal stresses in forged and hot-forged blanks

Internal stresses in forged or hot-forged blanks arise due to improper thermal processing, leading to defects such as cracks. These stresses are primarily caused by factors like uneven heating and cooling, failure to reach the optimal temperature for plastic deformation, or excessive temperature gradients within the material.

3.16.3 Internal stresses in welded blanks

Internal stresses in welded blanks primarily arise from uneven heating and cooling cycles, restricted thermal expansion and contraction, and phase transformations occurring during the welding process. Additional stress may result from welding dissimilar material thicknesses or from suboptimal selection of welding parameters and process conditions.

Moreover, further internal stresses can be introduced during subsequent machining operations. One specific cause is the roughening of the machined surface, which may lead to localized plastic deformation and residual stress buildup in the surface layer.

The magnitude of these machining-induced stresses depends on several factors, including cutting parameters, tool geometry, material properties, and the condition of the cutting tool.

Thus, internal stresses increase with:

- •reduction of cutting tool angle: smaller tool angles increase cutting forces and friction, causing more plastic deformation and higher residual stresses;
- •increase of cutting-edge radius: large nose radius raises contact area and heat generation, leading to greater plastic deformation and stress buildup;
- •higher feed rate: increased feed thickens the chip, raising mechanical load and temperature, which intensify residual stresses near the surface;
- •cutting speed above 300 m/min: higher speeds increase temperature, causing thermal softening and microstructural changes that elevate internal stress;
- •presence of vibrations: vibrations cause irregular cutting forces and uneven material removal, resulting in unpredictable residual stress formation.

After certain technological processes used in blank production, internal stresses are balanced, sometimes reaching high values.

•When a layer of material is removed (especially during rough machining), the internal stresses become unbalanced and redistribute within the part, leading to deformation.

•Unacceptably large deformations may sometimes be discovered during assembly.

•Parts experiencing significant internal deformation often become unusable.

Minimizing internal stresses in blanks

•The blank should be designed to minimize internal stresses.

•For cast blanks, a uniform cooling rate is essential. Sudden variations in cross-section, sharp corners, and other features that may cause uneven cooling should be avoided.

•For welded semi-finished products, the correct welding sequence must be selected to prevent excessive internal stresses. Additionally, pre-heating of welded blanks and stress-relieving heat treatments are commonly used.

Methods of stress relief in materials

Stress relief is essential in manufacturing to prevent deformations, cracks, or failures in components caused by internal tensions. There are two main approaches:

1. By natural means (natural ageing)

- Components such as beams, machine tool tables, and engine blocks are left to age naturally for 4 to 8 months between the roughing and finishing phases.
- During this period, internal stresses gradually relax due to temperature fluctuations and material creep.
- This method is effective but time-consuming and requires storage space.

2. Artificial stress relief methods

a. Heat treatment:

- Components are heated to a specific temperature (e.g., **500-650°C for steels**) and then slowly cooled.
- This allows internal stresses to redistribute and relax.
- Common processes include **annealing, normalizing, and tempering**.

b. Mechanical methods:

- Hammering (Peening): Controlled hammering of the surface introduces compressive stresses that balance internal tensions.
- Blasting: Shot blasting with small steel spheres helps redistribute stress and improve surface properties.
- Vibration Stress Relief (VSR): The component is subjected to controlled vibrations, allowing stresses to dissipate without altering material properties.

Tab. 2. Comparison of residual stress relief methods [5]

Method	Advantages	Disadvantages
Natural Ageing	No additional energy required, stable results	Long duration (months), space-consuming
Heat Treatment	Effective for most metals, well-established	Requires specialized equipment, energy-intensive
Mechanical Methods	Quick, cost-effective, no heating required	Less effective for all materials, requires expertise

3.16.4. Measures for reducing internal stresses

During machining, internal stresses can develop due to cutting forces, thermal effects, and tool-material interactions. The following measures can help minimize these stresses:

1.Adoption of light cutting regimes:

- Use **low cutting depths and feed rates**, especially in **finishing operations**.
- This reduces cutting forces and heat generation, which helps prevent excessive stress buildup and deformation.

2. Use of appropriate finishing tools:

- Finishing should be done with new (unused) tools to ensure sharp cutting edges.
- Tools should have large rake angles to reduce cutting resistance and deformation.
- The tool tip should have small radii to minimize vibrations and improve surface quality.

3. Cooling and lubrication for thermal stability:

- When thermal deformations are significant, cooling fluids (coolants or cutting oils) should be used.
- Different types of coolants can be selected based on the material and machining conditions:
    - ➢ **Water-based coolants** for high-speed cutting.
    - ➢ **Oil-based lubricants** for reducing friction and wear.
    - ➢ **Cryogenic cooling (liquid nitrogen)** for extreme precision applications.

The most appropriate method for eliminating internal stresses, both **after the production of semi-finished products** (by casting, forging, pressing, welding, or plastic deformation at high or low temperatures) and **during mechanical processing**, **is artificial stress relief**.

Why artificial stress relief?

During manufacturing processes such as **casting, forging, welding, and plastic deformation**, residual stresses develop due to:

- **Non-uniform cooling rates** (in casting and welding).
- **Material flow and grain distortion** (in forging and pressing).
- **Thermal expansion and contraction** (in hot and cold plastic deformation). **Mechanical forces** applied during machining.

If not eliminated, these stresses can lead to:

- Dimensional instability.
- Reduced mechanical properties.
- Cracking or premature failure of components.

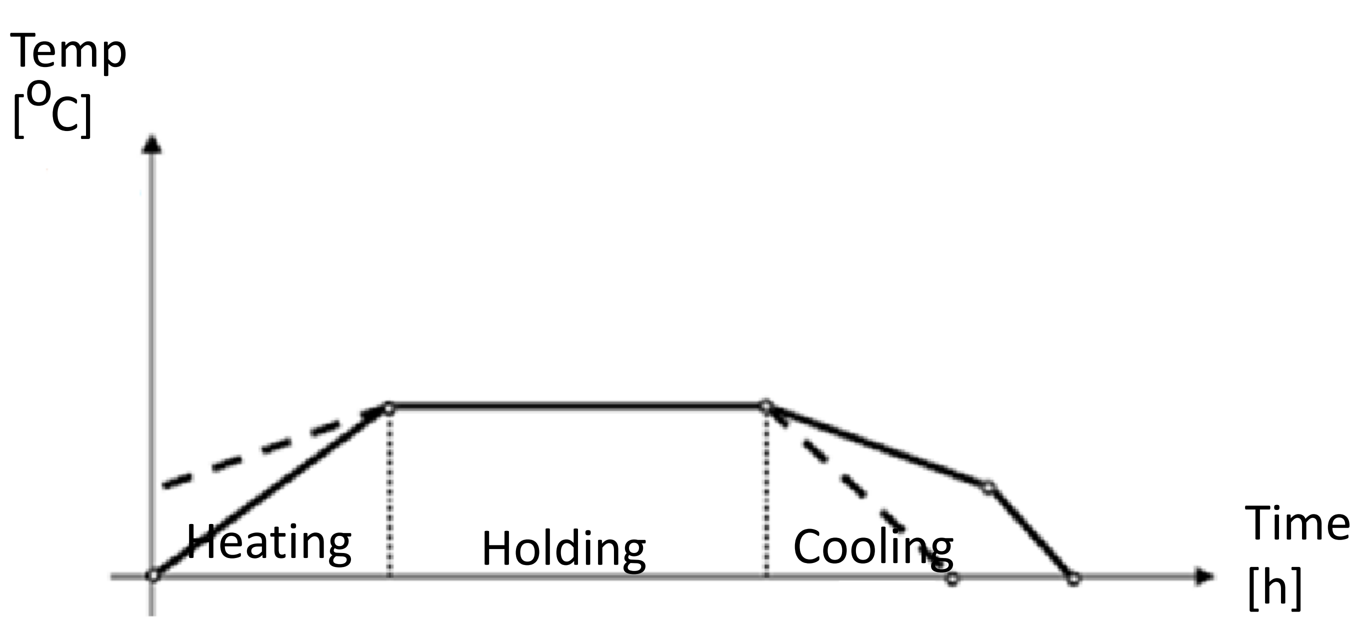


Fig. 25. General plot of the detensioning heat treatment [1]

Heat treatment for stress relief in steel

1. Heating process

- The material is **heated in an oven** designed for heat treatments.
- The heating rate is typically **40°C per hour**, ensuring uniform temperature distribution and preventing thermal shock.

2. Holding (soaking) phase

- Once the target temperature is reached, the material is **maintained in the oven** at that temperature.
- For steel, significant stress relief occurs from **450°C**.
- Almost complete stress relief is achieved at **600-650°C**, with a holding time of **4-6 hours**, depending on material thickness and composition.

3. Cooling process

- **Slow cooling** is necessary to prevent reintroducing internal stresses.
- This can be done by:
  - **Cooling in the oven** (gradually reducing temperature).
  - **Using a cooling medium**, such as a **molten salt bath**, which ensures controlled and uniform cooling.
- The cooling rate is usually **20°C per hour** to avoid thermal gradients that might cause stress buildup.

Low-temperature stress relief (detensioning)

1. When is it used?

Detensioning at lower temperatures (**150-250°C**) is applied to:

- **Chipping tools** (e.g., cutting tools, drills, milling cutters).
- **Cemented and hardened parts** (e.g., components subjected to heat treatments that must retain their hardness).

This process ensures that the material maintains its **high hardness and mechanical properties** while reducing internal stresses.

2. Stress relief for high-precision parts

- The higher the accuracy required for a part, the more stress relief must be done in **several intermediate steps**.
- This involves **annealing operations** at gradually lower temperatures (**120-150°C**) and with progressively longer holding times (**24-48 hours**).

3. Why is multiple-step stress relief necessary?

- Each stress-relief process introduces **small deformations** in the material.
- These deformations are corrected in subsequent **pre-finishing operations** (e.g., grinding, polishing).
- However, pre-finishing itself introduces **new internal stresses**, though of **lower intensity**.
- By repeating the process, internal stresses are gradually reduced without compromising the dimensional accuracy of the part.

Bibliography

[1] Ancău M., - Tehnologia Fabricației. Casa Cărții de Știință, Cluj-Napoca, 2003

[2] Berce P., - Tehnologia fabricării și reparării utilajelor tehnologice, Atelierul de multiplicat al Institutului Politehnic Cluj-Napoca, 1986

[3] Gyenge Cs., et al. – Tehnologia fabricării mașinilor, UTC-N, 1991

[4] Frățilă D., et.a – Tehnologii de fabricație, Îndrumător de lucrări de laborator, U.T. Press 2011

[5] Radu S.A – Tehnologii de Fabricație – Suport de curs – UTPRESS, Cluj-Napoca, 2019, ISBN 978-606-737-368-4.

[6] 10/07/2024 Cutting Chips in Machining: A Mine of Information! - Nakamura-Tome Cutting Chips in Machining: A Mine of Information!

[7] Increasing tool life by reducing the cutting sp... | Holooly

[8] Zhuang K., Huang Y., Cheng H., Wang J., - An improved approach to tool life promotion concerning cutting edge microgeometry, The International Journal of Advanced Manufacturing Technology 126 (3-4):1-15, March 2023.