MAINTENANCE OF STEEL MILL ROLLS
FOR FLAT ROLLED PRODUCTS
BY ROLL TURNING

By

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ABSTRACT

The thesis investigates roll turning for the maintenance of steel mill rolls at DOFASCO and culminates in the specification of a roll turning lathe. The thesis can basically be divided into three main categories:

(1) The application of steel mill rolls for both hot and cold rolling processes, their requirements and characteristics.

(2) Present roll maintenance practices and machinery. All rolling mill rolls require a regular redressing to restore the specified surface quality and the specified cylindricity which is necessary to produce a high quality product. Roll surface conditions prior to machining are of particular interest. A new approach to the maintenance of steel mill rolls is investigated. This is the replacement of roll grinding, which is generally applied throughout the steel industry, by roll turning.

(3) The economic justification for roll turning leads to the development of specifications for the selection and procurement of a roll turning lathe for the maintenance of steel mill rolls at DOFASCO.

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D = Roll Diameter, mm

E = Modulus of Elasticity, MPa

F = Roll Separating Force, MN

L = Projected Length of Roll Contact, mm

R = Roll Radius, mm

Y = Yield Strength - Uniaxial Tension, N/mm^2

$\bar{b}$ = Mean Width of Ingot, mm

f = Horizontal Forces Acting On Elemental Slice of Material in the Arc of Roll Contact

f_n = Speed Correction Factor

h_0 = Annealed Strip Thickness, mm

h_1 = Thickness of Material Before Pass, mm

h_2 = Thickness of Material After Pass, mm

h_3 = Thickness of Material Leaving #2 Stand and Entering #3 Stand of a Multi-stand Mill, mm

$\bar{h}$ = Mean Thickness, mm

Δh = Reduction of Thickness, mm

k = Shear Stress Transmitted Between Roll and Material

$2k$ = Yield Stress in Plane Strain Conditions, N/mm^2

$\overline{2k}$ = Mean Yield Stress in Plane Strain Conditions, N/mm^2

k_v = Roll Force Coefficient

n = Speed of Work Rolls, r/min

p, q = Principal Stresses

P_c = Contact Pressure Between Work Roll and Back-up Roll, MPa

Ps = Specific Roll Pressure, (eg) Roll Force per Unit Area of Contact Surface, MPa

r = Linear Reduction in a Pass = $\frac{h_1-h_2}{h_1}$

$\bar{r}$ = Mean Linear Reduction in a Pass

r_1 = Pre-reduction, (eg) Total Reduction Before Pass of Annealed Strip

r_2 = Total Reduction After Pass of Annealed Strip

r_3 = Total Reduction After Pass of Annealed Strip Leaving #2 Stand and Entering #3 Stand of a Multi-stand Mill,

$= \frac{h_0-h_3}{h_0}$

s = Roll Pressure - Normal to Roll

t = Temperature, ^oC

v = Strip Velocity, m/min

v_1 = Entry Velocity Strip, m/min

v_2 = Exit Velocity Strip, m/min

w = Width of Strip, mm

ϕ = Angle Between Transverse Element and Roll Centre Line

ω = Angular Velocity

CHAPTER VI

A = Chip Cross Section, mm^2

A_s = Roll Surface Area, mm^2

C = Workpiece Material Constant, N/mm^2

C_T = Cutting Tool Constant, $mm^2/min.r$

C_{Tool} = Cutting Tool Related Costs, \$

$C_{Cut\ Edge}$ = Costs per Cutting Edge, \$/edge

C_{Tot} = Total Cutting Tool Related Costs, \$

F_v = Main Cutting Force in Velocity Direction, N

F_r = Radial Cutting Force, N

F_f = Cutting Force in Feed Direction, N

F_s = Specific Cutting Force, N/mm^2

L_m = Machining Length, mm

P_c = Power at Cutting Tool, kW

P_{mot} = Power at Motor, kW

Q = Metal Removal Rate, cm^3/min

R_T = Tool Nose Radius, mm

T = Tool Life, min

T_{opt} = Optimum Tool Life, min

T_{max} = Maximum Torque, N.m

a = Depth of Cut, mm

b = Chip Length, mm

c = Workpiece Material Constant

d = Roll Diameter, mm

h = Chip Thickness, mm

n = Rotational Speed, r/min

n_{Lim} = Limiting Speed at T_{max} and P_{max} , m/min

p,q = Tool Characteristics

P_s = Specific Cutting Edge Load, N/min

r_m = Machine Rate, Including Wages and Overhead Costs, $/min

s = Feed Rate, mm/r

t_m = Machining Time, min

t_{tch} = Tool Change Time, min

t_{Tot} = Total Machining Time, min

v_c = Cutting Speed, m/min

α = Top Rake Angle

β = Wedge Angle

γ = Clearance Angle

λ = Back Rake Angle

ε = Plan Angle

χ = Approach Angle

η = Machine Tool Efficiency

CHAPTER VII

C = Resulting Machine Tool Compliance, mm/N

F_r = Radial Cutting Force, N

F_s = Specific Cutting Force, N

K = Machine Tool Stiffness, N/mm

R_c = Cutting Force Stiffness, N/mm

a = Depth of Cut, mm

y = Radial Deflection Between Tool and Workpiece, mm

μ = Ratio of Cutting Force Stiffness to Machine Tool Stiffness

δ = Remaining Form Error After Cutting, mm

Δ = Initial Form Error Before Cutting, mm

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INTRODUCTION

Dominion Foundries and Steel Ltd. is Canada's second largest fully integrated steel producer. It is an extremely successful business enterprise which introduced the revolutionary oxygen steel making process to North America.

Dofasco produces flat rolled products only. These include hot rolled, cold rolled, tin plate, silicon, chromized, galvanized and pre-coated steel. The company presently employs 13,000 people and produced over 4 million ingot tons in the fiscal year 1979 with sales exceeding $1.4 billion.

The maintenance of all mill components is important for an efficient operation of a rolling mill. However, the most critical components with respect to the rolling process are the rolls and the maintenance of rolls. Of primary concern is the influence of rolls on the rolled product. Improper roll application (e.g. improper selection of roll materials) or maintenance procedures result in roll surface damage. These damages are transfered to the rolled material resulting in product reject and immediate removal of these rolls. Mill down time caused by frequent roll changes reduces mill productivity. Improper selection of roll materials also results in the lowering of roll life, and consequently in high replacement costs and roll maintenance costs.

Roll costs represent the single largest consumable item in the operating budget of rolling mills. Roll inventory replacement cost of DOFASCO's Hot Mill rolls approach $10 million and yearly roll replacement costs are over $5 million. Cold mill roll costs are equally as high. Changes in roll maintenance practices or changes in roll materials can therefore lead to substantial cost reductions. This is illustrated in Section 4.2 where it is shown that a change in roll maintenance practices resulted in a hot mill back-up roll life extension of over 200%.

The equipment required to maintain these rolls represents another high expense. The cost to install an average sized roll grinder with a capacity to grind a roll of 1000 mm diameter and a 5000 mm length is approximately $1 million.

Roll grinding machinery with an approximate replacement value of $20 million is installed at DOFASCO for the maintenance of hot and cold mill rolls.

An operating budget of approximately $10 million is required to cover the costs incured through labour and overhead expenses of the roll maintenance departments. Due to the very high hourly operating cost, even small changes in productivity have a tremendous effect on costs.

In the mid-seventies extensive testing at DOFASCO was undertaken to investigate the feasibility of maintaining hot mill back-up rolls by turning, rather than by grinding, which is commonly applied in the steel industry. The result of the tests showed that the surface roughness and integrity of a turned roll was sufficient to ensure the surface quality of the rolled steel strip. This led to a subsequent investigation into the economics of using a roll turning lathe for the maintenance of steel mill rolls.

The metal removal capability of turning commercial grade steels (eg. S.A.E. 1010) is very much higher than by grinding. The grinding process is generally chosen for machining very hard materials and for the purpose of achieving a surface finish which is very much superior to turning. Due to the relative high hardness of rolling mill rolls and consequently the lower metal removal rate by turning, comparative machining time studies were conducted to determine the economic feasibility of turning mill rolls. Despite the high roll hardness it was found very advantageous to use turning for heavy steel mill rolls (Chapter V).

Due to the limited surface finish achievable by turning, as compared to grinding, only the machining of heavy rolls was considered in this investigation. These heavy rolls do not require the high surface finish. The rolls considered include slabbing mill rolls, hot strip mill back-up rolls and the repair of cold mill back-up rolls. All cold mill rolls and hot strip work rolls require a high degree of surface finish which is beyond the capability of the turning process. A repaired cold mill back-up roll must therefore, be finished by grinding after turning.

The subsequent chapters are arranged in a logical sequence, starting with the steel mill roll application and ending with the objective, which is the specifications for a roll turning lathe.

CHAPTER I

ROLL APPLICATIONS

1.1. Basic Principles of Rolling Steel

The simplest method of shaping steel is by rolling. This process consists of passing the material between two rolls, called work rolls. The rolls are revolved at the same peripheral speed and in opposite direction; i.e. clockwise and counterclockwise . The distance between the rolls, called roll gap, is smaller than the thickness of the steel which is to pass between them, as illustrated on Figure 1.0.

Under these conditions, the rolls grip the material, deform it and reduce its cross sectional area, e.g. a reduction in thickness which results in an elongation of the rolled material .

On large cross sectional reductions and cross sectional shapes having smaller width-height ratios, such as is typical for reducing ingots, the sideway elongation of the material, called "spread" has to be considered. This sideway spread is controlled by additional rolls set vertically to restrain the edges, see Figure 1.0.

Wide strips and high loads may make the rolls deflect quite considerably due to the imposed bending, so that the rolled strip deviates from the required flatness. This factor and the advantage of using smaller diameter rolls, which results in lower roll separating forces and consequently in less massive equipment, led to the use of four high mills in which the work rolls are being backed up by larger diameter rolls, called back-up rolls, see Figure 1.1.

Important characteristics of rolling are changes in deformation velocity and directional changes of friction forces acting on the rolls. These changes occur within the deformation zone and are important factors in understanding the wear process on work rolls. This will be further discussed in more details in Section 3.2.

Due to the reduction in material thickness from h_1 to h_2 , the exit velocity v_2 must be considerably higher than the entry velocity v_1 . The peripheral velocity of the work rolls will have to have some value between v_1 and v_2 . This means that the roll surface at the entry side of the strip is moving faster than the material and slower than the material at the exit side. The frictional forces acting on the material at exit and entry will be in opposite directions.

Frictional forces at the entry side, force the material through the mill towards the exit side. As the material passes through the deformation zone in the mill at increasing speed there is a point where $v_{strip} = v_{roll}$ and there is no relative movement between roll and material. This is the so called neutral point. The frictional force at the neutral point is zero. Frictional forces at the exit side oppose the material flow. They are directed towards the entry side.

1.2 Large and Small Scale Deformation Processes

1.2.1 Hot Rolling

There are two basic rolling deformation processes; large and small scale. The large scale deformation process is called hot rolling, as the steel is heated up to approximately 1,260°C before rolling commences. Large dimensional reductions are possible at these temperatures, due to the low yield strength of the heated material.

The manufacturing sequence of hot rolling flat products at DOFASCO is first to reduce the ingot in a slabbing mill, where the ingot is reduced from approximately 700 mm to 250 mm in height. It then is passed on to the intermediate roughing mill for further reduction from approximately 260 mm to 30 mm. The final reduction to approximately 2.5 mm is made by the finishing mill, consisting of 7 stands.

The hot rolled product can be further reduced by cold rolling.

1.2.2 Cold Rolling

Cold mills are used to produce a product that is thinner, of higher dimensional accuracy, with a smoother surface and with a higher strength-weight ratio than is possible by hot rolling. The material enters the cold mill at room temperature. The dimensional reduction is consequently of a smaller scale, due to the high yield strength of the cold material. Cold reduction mills are used either as single or as multistands. Most modern installations are of 5 stands arranged in a row.

1.3 Hot Mills

1.3.1 Slabbing Mill

After the ingots are heated uniformly to a rolling temperature of approximately 1,300°C they are reduced from ingot size of approximately 610 mm to 760 mm x 1,270 mm to 1,780 mm cross section to a so-called slab having an oblong cross section.

The slabbing mill of DOFASCO produces 230 mm to 280 mm thick slabs. This slabber is equipped with two horizontally placed work rolls, 1,140 mm diameter x 2,235 mm roll barrel length. Edger rolls, vertically placed, are attached at the mill entry side, see Figure 1.0. The edger rolls, 1,143 mm diameter x 1,070 mm roll barrel length, are driven by a 1,500 kW DC motor. The work rolls are powered by twin 2,240 kW DC motors. The mill, having 2 work rolls, one over the other, is termed a 2 Hi Mill. A slabbing mill with added edger rolls is called a universal 2 Hi Mill.

The large amount of reduction in the thickness of the material is achieved by passing the ingot through the roll gap, reversing the rolls and passing it through again in the reverse direction. This reversing action continues until the material has been reduced by the desired amount.

1.3.1.1 Elementary Assessment of Roll Loads

Theoretical calculations of the hot rolling loads are approximations due to the ill defined dependancy of the yield stress on variables such as temperature, rate of straining and frictional conditions between rolls and material.

The most simple method of obtaining roll loads is to assume a deformation process with homogeneous compression between well lubricated platens as described in Reference [1].* The load F required to compress the strip is:

$$F = YLw \qquad (1)$$

whereby Lw is the projected area of compression and w = width of strip. From the geometry of Figure 1.4, L the projected length of contact can be easily expressed by using the roll radius R and the amount of reduction Δh.

$$L = \sqrt{R^2 - (R - \tfrac{1}{2}\Delta h)^2} = \sqrt{R\Delta h - \tfrac{1}{4}(\Delta h)^2} \simeq \sqrt{R\Delta h} \qquad (2)$$

The yield strength Y is difficult to obtain and depends on the effect of friction, spread, rolling speed and most important, the temperature.

An approximate yield stress for carbon steels can be obtained by calculation using a formula provided by S. Ekelund (from Reference [2]). For this purpose, a deformation rate of nearly zero was assumed. The strain rate, however, does have a great effect on the yield stress. Wusatowski [2] deals with this in detail. The strain rate effect is accounted for

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* Numbers in square brackets indicate references given in Bibliography.

in the roll load calculation derived from practical mill observations. These experimentally compiled data yield far more satisfactory results than any theoretical treatments. The following Section 1.3.1.2, considers strain rate effects. Ekelund's equation applies for steels of up to 600 N/mm^2 strength and for a temperature range of 800°C to 1,300°C.

$$Y = .147\ (1400 - t) \quad (N/mm^2) \qquad (3)$$

whereby, t is the temperature in °C to which the steel is heated.

Roll load calculations are shown on Tables 1 and 2 for a typical average sized ingot of SAE 1010 material.

1.3:1.2 Calculation of Roll Separating Force

Most theoretical equations and empirically obtained methods to calculate the roll force do not provide satisfactory results. Actual measurements taken at several steel works and institutions produced a family of graphs which allow the calculation of roll forces far more accurately than any theoretical treatment.

These graphs give the specific roll pressure p_s as a function of the linear reduction $r = \frac{h_1 - h_2}{h_1}$ and the parameter h_1/D. The specific roll pressure is defined as the roll separating force per unit area of contact surface. For each grade of steel there are graphs for different temperatures, and a given speed, see Figures 1.2 and 1.3 of

Reference [3] .

SKF [3] accounts for the effect of the strain rate in their speed factor f_n. This speed factor is shown on Figure 1.3 and is a function of the rolling speed and temperature. SKF states that these values are approximated because of test conditions which differ considerable from actual rolling conditions. An increase in the strain rate in hot rolling results in an increase of the yield stress if the rolling temperature remains constant.

As seen in Section 1.3.1.1 the roll separating force F is basically a product of the projected area between the rolls and material and the specific roll pressure s. From Reference [3] the roll force is being calculated as follows:

$$F = f_n \overline{P_s} \overline{b} \sqrt{R\Delta h} = f_n \overline{P_s} \overline{b} \sqrt{Rrh_1} \quad (4)$$

whereby f_n = correction factor for speed; $\overline{P_s}$ = mean value of specific roll pressure; $\overline{b}$ = mean width of billet; and, R = roll radius.

1.3.1.3 Frictional Forces on Roll

Figure 1.4 shows the deformation process, the stress and forces acting on two elements on each side of the neutral plane. Both Rowe [1] and Alexander [4] discuss this simplified model in detail. It is based on several assumptions and can only be considered as an approximation of the actual occurrences within the deformation zone.

The stress p, assumed to be uniformly distributed, and the vertical stress q are principal stresses. The pressure normal to the roll is designated as s and the shear stress transmitted between roll and slab is k.

An analysis of forces is shown on the two elements and an equation of horizontal forces equilibrium was obtained by Alexander and Brewer [4] and is:

$$\delta f = 2\ s\ R\ \delta\phi\ \sin\phi \pm 2k\ R\ \delta\phi\ \cos\phi \qquad (5)$$

The first component of the right hand side of the equation is generated by the radial pressure on both rolls. The second components represent the frictional forces acting on the rolls. As can be seen from Figure 1.4, the frictional forces reverse directions at the neutral plane. The negative sign appearing in the above equation refers to conditions on the entry side in relation to the neutral plane and the positive sign refers to the exit side conditions. This phenomena is important in order to understand the major cause of wear on work rolls. In rolling narrow stock such as ingots, a considerable amount of spreading takes place during the rolling. This introduces further frictional forces which are transverse and are directed towards the centre of the slab.

1.3.1.4 Roll Pressure Distribution

The roll pressure s, varies from entry to exit due to the frictional contribution. The friction forces increase the roll load necessary for the deformation of the material.

The roll pressure distribution resulting from the simple theory by Alexander and Brewer [4] is shown on Figure 1.6.

A more complex pressure distribution was developed for hot rolling of narrow stock such as ingots. A considerable amount of spreading takes place during the rolling of ingots. This introduces further frictional forces which are transverse and are directed toward the centre of the slab. This modifies the simple pressure distribution to the more complex shape as illustrated on Figure 1.5. The assumption of the simple theory that the deformation takes place under plane strain conditions is invalid.

The hill shaped pressure distribution is known as "Friction Hill". From this the roll separating force was developed by Orowan(from Reference [4]).

He simplified his investigation by replacing the curved surface of the roll with flat parallel platens and then proceeded to calculate the pressure distribution s. By considering the volume of the friction hill, as shown on Figure 1.5, he finally obtained an equation for the total roll load, which is:

$$F = 2k\bar{b}L\left[0.8 + 0.5g - \frac{\bar{h}}{3\bar{b}g}(g - 0.2)^3\right] \quad (6)$$

where: 2k = Yield Stress

$\bar{b}$, mean width of stock = $\dfrac{2b_2 + b_1}{3}$

$\bar{h}$, mean thickness = $\dfrac{2h_2 + h_1}{3}$

$$g = 0.5L/h_2$$

Roll Load calculations are shown on Table 1 and 2 for a typical average sized ingot of SAE 1010 material.

1.3.2 Intermediate Roughing Mill

This 2 Hi universal mill receives 230 mm to 280 mm thick slabs from the slabbing mill and reduces them to 25 mm to 38 mm thickness. The work roll size is 978 mm diameter x 1,680 mm barrel length, with edger rolls of 762 mm diameter x 864 mm length. The edger rolls are attached at the entry side of the mill. The main mill is powered by a single 6000 kW DC motor and the edgers by a 2,350 kW DC motor.

The same principles concerning roll separating force, frictional forces and pressure distribution apply to this mill as previously discussed in Section 1.3.1.2 to 1.3.1.4.

1.3.3 Finishing Mill

The Dofasco finishing mill consists of 7 stands and reduces the 25 mm to 28 mm thick steel strip from the intermediate roughing mill to an approximate average thickness of 2.5 mm. Strip width ranges from approximately 1000 mm to 1520 mm. The strip enters the first finishing stand at an approximate temperature of 1100°C and exits at approximately 800°C.

All 7 stands are of 4 Hi construction with a work roll size of 724 mm diameter and a back-up roll size of

1320 mm diameter, see Figure 1.1. Both rolls have a barrel length of 1676 mm. The strip speed ranges from 60m/min in #1 finishing stand to 730m/min at the #7 finishing stand.

1.3.3.1 Elementary Assessment of Roll Loads

The rolling in the finishing stands of wide strips and relatively small thicknesses results in negligibly small amounts of spreading. Plane strain conditions can therefore be assumed, which changes the simple equation (1) as follows:

$$F = 2k\ Lw \qquad (7)$$

whereby 2k, the yield stress in plane strain = $\frac{2}{\sqrt{3}}$ Y according to von Mises' theory.

The yield stress Y can be obtained from equation (3).

1.3.3.2 Calculation of Roll Separating Force

A more accurate calculation of the roll force can be obtained in the same manner as outlined in Section 1.3.1.2.

1.3.3.3 Frictional Forces on Rolls

The frictional forces on the work rolls generated by the deformation process of this 4 Hi mill are identical to those described in the previous Section 1.3.1.3. Due to the 4 Hi construction of the mill, there are on occasions additional frictional forces which are generated between the work rolls and back-up rolls. The work rolls are powered and the back-up rolls are driven by the work rolls. Relative motion or so called skidding is possible between the rolls, particularly during mill deceleration and acceleration.

Back-up roll wear is very much less than that experienced on work rolls. The more severe wear conditions on work rolls are due to the previously described large frictional forces on the rolls generated by the deformation process.

1.3.3.4 Roll Pressure Distribution

The rolling of wide strips results in very small amounts of spreading and one can assume plane strain conditions. This leads to a relatively simple pressure distribution which is shown on Figure 1.6. Alexander and Brewer [4] presented the development of the pressure distribution and roll force calculation in detail. From their simple "Friction Hill" (Figure 1.6), the roll force per unit width was developed and is given by the equation:

$$F = 2k\,L\left(0.8 + \frac{L}{4h_2}\right) \qquad (8)$$

The maximum value of the pressure distribution is not necessarily placed at $\frac{L}{2}$, however, Orowan's investigations showed that this can be assumed without much loss in accuracy.

Roll load calculations are shown on Table 3 and 4 for a typical average sized strip of SAE 1010 material.

1.4 Cold Mill

After the hot rolling process is completed, the sheet steel is cleaned (pickled) in a bath of sulfuric or hydrochloric acid. The surface oxide, commonly known as scale, which forms during the hot rolling is removed by the pickling process. The coils of pickled hot rolled steel are then reduced in cold mills in order to produce a product with thinner gauge, higher surface quality and with a higher strength to weight ratio.

The steel to be rolled is at ambient temperature. It is not heated as is the case in hot rolling.

The typical basic construction of a cold mill is 4-High. Two work rolls are supported by two back-up rolls, stacked four high, see Figure 1.1.

There are several single stands and two 5 stand tandem or continuous mills in service at DOFASCO. The smallest single stand consists of 470 mm work roll diameter and 1100 mm back-up roll diameter. Mill width, corresponding to roll barrel length is 1070 mm. Average mill speed is 520m/min This particular mill is a reversing mill. Once the sheet is reduced, it will be re-rolled and further reduced by reversing the rolling direction until the desired reduction is achieved.

The largest and most modern mill is a 5 Stand continuous 4 Hi Cold Mill with 610 mm diameter work rolls and 1540 mm diameter back-up rolls. Mill width is 1830 mm. Maximum mill speed at #5 Stand is 1530 m/min versus 770 m/min at #1 Stand. Each stand is equipped with a 6000 kW DC motor.

driving the work rolls.

1.4.1 Roll Loads in Cold Rolling

All above mentioned aspects of rolling are basically similar to those of hot rolling, as discussed in Sections 1.3.3.1 to 1.3.3.4. The resistance to deformation is of course very much higher in cold rolling than in hot rolling.

During the cold rolling process the strain hardening of the material results in increased yield strength of the material at the end of the deformation zone. The roll pressure in cold rolling is generally reduced by applying tension on the strip. This tension is applied with the pay-off reel on single stands. Tension is applied between each of the stands in a multistand continuous cold reduction mill. Because of the very high contact pressure between roll and strip the effect of the elastic roll deformation must be considered in cold rolling. The purpose of this investigation, however, is only to highlight the basic differences between roll loads generated by cold rolling versus hot rolling in order to select the proper material for work and back-up rolls. For these load comparisons a more elementary calculation suffices.

1.4.1.1 Elementary Assessment of Roll Load

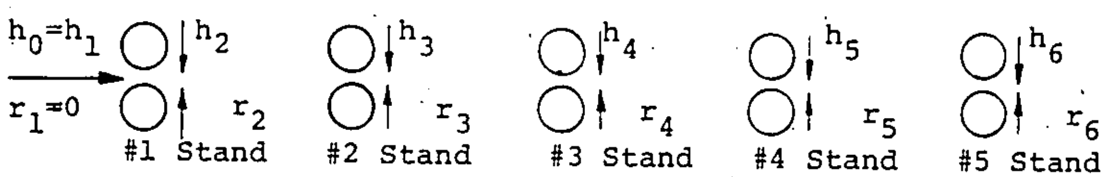
Due to the work hardening of the material during the rolling process, a mean value of the plane strain yield stress is required. The British Iron and Steel Association has developed diagrams giving the yield stress under plane compression, one of which is reproduced in Figure 1.7. SKF [3] shows that the mean reduction $\bar{r}$ required to obtain the mean yield stress $\overline{2k}$ during the pass can be calculated as:

$$\bar{r} = 0.4\ r_1 + 0.6\ r_2 \qquad (9)$$

$$\text{when} \quad r_1 = \frac{h_0-h_1}{h_0} \quad \text{and} \quad r_2 = \frac{h_0-h_2}{h_0}$$

The annealed strip thickness h_0 corresponds to h_1 for all products directly processed from the hot strip mill.

For the calculation of DOFASCO's 72"-5 Stand continuous cold mill, the mean reduction has to be calculated for each stand - see below:



The total reduction of the annealed strip before passing through the mill is:

$$r_1 = \frac{h_0-h_1}{h_0} \quad \text{and since} \quad h_0 = h_1$$

(fully annealed from the hot mill),

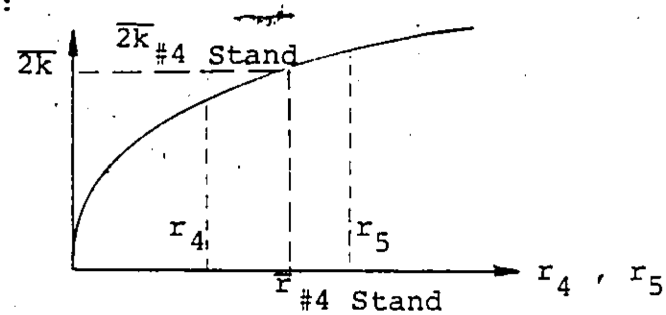
$$r_1 = 0 \quad \text{and} \quad r_2 = \frac{h_1-h_2}{h_1}\ ,\ \ldots\ldots\ r_6 = \frac{h_1-h_6}{h_1}\ .$$

The mean reduction per mill stand is calculated as follows:

$$\bar{r}_{\#1\ Stand} = 0.4\ r_1 + 0.6\ r_2 \quad \cdots$$

$$\bar{r}_{\#5\ Stand} = 0.4\ r_5 + 0.6\ r_6\ .$$

The mean yield stress is obtained from Figure 1.7, as shown below:



Roll Load F is:

$$F = \overline{2k}\ Lw \tag{10}$$

The influence of strip tension on roll load was omitted. Roll load calculations are shown on Table 5 for a typical average sized sheet of SAE 1010 material.

1.4.1.2 Calculation of Roll Separating Force

Most theoretical methods of calculating roll forces do not lead to entirely satisfactory results. Actual measurements taken at several steel works and institutions produced a family of graphs which allowed the calculation of roll forces to be more accurate, see Figure 1.8. As per SKF [3], the roll force F without strip tension equals:

$$F = k_v wD \tag{11}$$

whereby w = strip width and D = roll diameter. k_v is the roll force coefficient when rolling without strip tension. This coefficient is a function of the thickness ratio

$$\frac{h_1}{D}$$

the pre-reduction (total reduction before pass of annealed strip) e.g.:

$$r_4 = \frac{h_0 - h_4}{h_0}$$

and the reduction r of the pass in the individual stand. Roll load calculations are shown on Table 5 for a typical averaged sized sheet of SAE 1010 material.

1.5 Load Comparison Between Hot Rolling and Cold Rolling

A comparison is made of roll loads when rolling 0.1% C commercial grade steel. The purpose of this exercise is to establish the mechanical loading on the rolls themselves. This is essential in order to choose the proper roll material for a particular roll application.

For the load comparison in hot rolling, the 88" Slabbing Mill (Section 1.3.1) and a 7 Stand continuous finishing mill (Section 1.3.3) are selected.

The most modern 5 stand continuous mill 610 mm diameter x 1540 mm diameter x 1830 mm width is selected for the calculation of cold reduction rolling loads.

1.5.1 Results - Hot Rolling

The results of the different methods of calculating roll separating forces in hot rolling are shown on Table 1 to 4, those of cold rolling in Table 5. These theoretically obtained values are compared with actual roll separating forces, as recorded from mill operation.

The roll load of the elementary assessment method, as per Section 1.3.1.1 is very low compared to the figures actually recorded in the mill. There are several factors which have not been included in the elementary assessment, which have a drastic influence on the roll force magnitude. Some of these are: rate of deformation (rolling speed), substantial differences in roll pressure due to frictional forces, and inaccuracy in obtaining the yield strength of the material at elevated temperatures. All above mentioned factors increase the rolling load.

Roll separating force calculations as per Section 1.3.1.2 are very close to the actual values obtained and can be considered as very satisfactory. This method of roll load calculation is based on actual measurements taken at several steel works and institutions. The more elaborate theoretical model, developed by Orowan (from Reference [4]). led to disappointing results. The influence of frictional forces and spreading of the rolled material is included in this theory.

The friction hill generated, under actual slabbing and roughing mill conditions, could be very much larger than the theoretical values due to the very rough surfaces of the slabbing mill rolls. These rolls are firecracked, (refer to CHAPTER III). Surface cracks typically 1.5 mm wide x 12 mm deep x 50 mm long cover the complete roll body. The cracks have both radial and circumferential orientations and generate very large frictional forces.

The theories of rolling in general and in particular the elementary assessment of roll loads are inadequate when compared to practical observations. To improve the accuracy of roll load calculations, both for hot and cold rolling, one must continue to compile data of actual mill performances of modern mills. This experimentally obtained information must be correlated to existing methods for the calculations of roll loads. The collection and refinement of data is important since mill performances can vary substantially, even between apparently similar mills.

1.5.2 Results - Cold Rolling

Table 5 shows the comparison of roll separating forces and roll pressures of the 72" continuous cold reduction mill based on different calculations. The effect of strip tension on roll load was not considered. The loads obtained by the elementary assessment are lower than the actual roll loads.

This was also the case in hot rolling. However, the difference in cold rolling is not as large due to the reduction of the actual roll loads caused by the strip tension.

If strip tension had been included in the theoretical calculations, the difference would have been more substantial.

The calculation of the roll separating force as per Section 1.4.1.2 resulted in loads higher than the actual load. This was expected. These values would be reduced if the effect of strip tension and speed would be included in the calculation.

1.5.3 Comparison

For the selected mills using a commonly rolled grade of material and an average product size, the following summary can be made based on Tables 1 to 5:

TYPE OF ROLLING MILL	FORCE (MN)	PRESSURE (MPa)
Hot Rolling Mills:		
Slabbing Mills	10 - 11	40 - 45
Finishing Mills	5 - 12	150 - 350
Cold Mills:	6 - 10	600 - 2200

The magnitudes of roll separating forces and roll pressures are approximate but show very clearly the different loads on the various mill rolls. Rolling mill roll selection is based on these figures. Further details are shown in the following CHAPTER II dealing with roll material and hardness.

CHAPTER II

ROLL MATERIALS AND HARDNESS

The mechanical properties of the roll material can be determined from the results of the roll load calculation. However, because of the widely varying mill conditions, roll selection usually proceeds on an empirical basis. Recent roll trials at DOFASCO and various other steel mills in North America confirmed this. High chrome work rolls (approximately 15% Cr., 60 to 75 Shore C hardness) were tested in hot strip mills with widely varying results. Some mills achieved 100% improvement in roll life. The same rolls failed catastrophically in other mills, offsetting any gains made by reduced roll wear, making further applications uneconomical. It is said by many experts that roll selection is an art rather than a science.

In addition to the mechanical strength of rolls, other properties are required such as resistance to wear, spalling and others, as outlined in CHAPTER III.

2.1 Slabbing Mill Rolls

The slabbing mill and intermediate roughing mill are both of 2 Hi construction. Since these work rolls are not supported by back-up rolls, they must be designed to take relatively high roll separating forces, see Table 1 and Section 1.5.3. These rolls require strength to withstand roll forces up to 22 MN. Due to this requirement and the objective to use small roll diameters, which minimizes the roll separating force and results in less massive mill equipment, most modern two high reversing mills use alloyed cast steel rolls [7]. The carbon content ranges from 0.8 to 1.3%. The usual alloying elements are about 1% chromium, 0.25 to 0.5% molybdenum and varying amounts of nickel depending on the particular application.

Roll pressure at the contact surface between the deformed material and the roll is very low, typically 40 - 45 MPa (Table 2). Cold mill work rolls in comparison are designed to withstand 600 to 2200 MPa roll pressure (Table 5). A relatively low surface hardness can be utilized due to the low roll pressure, and the ability to tolerate some roll wear by virtue of low accuracy requirements of the rolled slabs. The roll surface hardness of DOFASCO's rolls is 38 - 40 Shore (Scleroscope C) hardness, see Table 6.

More important than wear resistance of slabbing and roughing mill rolls is the resistance against fire cracking and most important the resistance to the propagation of fire cracks. Fire cracking is caused by the excessive thermal stress cycling developed during the rolling process, see Section 3.5.

Exposure to a number of heating and cooling cycles of the roll surface will inevitably lead to surface cracks, called fire cracks.

2.2 Hot Strip Mill Back-up Rolls

Large diameter back-up rolls are used to support the work rolls and prevent them from bending under the heavy rolling loads. The roll contact pressures between work roll and back-up roll are much larger than those developed within the deformation zone between the work rolls. These pressures can be calculated according to Hertz's theory [12]. Assuming that the modulus of elasticity of the work roll equals that of the back-up roll one can calculate the pressure as follows:

$$P_{c\ max} = 0.59\sqrt{\frac{F}{w}\ E\ \frac{D_1+D_2}{D_1 D_2}} \qquad (12)$$

for $E = 207 \times 10^3$ MPa, $D_1 = 724$ mm, $D_2 = 1650$ mm, $w = 1200$ mm and $F = 11$ MN (From Table 3, Pass 4).

The roll contact pressure between back-ups and work roll is 1145 MPa versus 338 MPa pressure between the work rolls. Approximate roll pressure on the 88" Slabbing Mill work rolls in comparison is 42 MPa (Table 1).

The wear resistance of the hot strip mill back-up rolls must be increased to accomodate these higher pressures and more importantly, the closer tolerance requirements of the rolled strip. Cast steel rolls are usually selected with a 40 to 50 Shore (Scleroscope C) hardness and carbon content of 0.8 to 1.0%, see Table 6.

Very good results were obtained by using differentially hardened cast steel back-up rolls. Linhart [8] shows substantial increases in roll life over conventional cast steel rolls. The differential heat treatment method is a process which develops a high - hardness and wear resistant outer roll shell and a tough inner core giving the roll body strength against roll breakage. Typical hardness ranges between 60 to 65 Shore (Scleroscope C).

2.3 Cold Mill Back-up Rolls

The necessity of good surface finish on the rolled strip and the high speeds, tolerance and shape requirements of modern cold rolling mills resulted in the usage of forged alloyed steel rolls for both work roll and back-up roll applications.

The hardness of DOFASCO's work rolls range between 93 to 98 Shore (Scleroscope C), the hardness of the back-up roll is 58 to 63 Shore, see Table 6.

In most rolling mills there is some risk of material passing between work and back-up roll causing damage to the rolls. It is preferable in these circumstances that damage occurs to the back-up rolls. If the work rolls are damaged, the indentations on the roll will be transfered to the rolled material. For this reason, the back-up rolls are therefore lower in hardness. The high hardness of work rolls results in a high resistance to surface wear and surface damage.

Roll pressures between back-up and work roll of the 72"-5 Stand Cold Mill (as per Table 5) using Hertz's formula (Equation 12) is approximately 1200 MPa.

A typical material analysis of these back-up rolls consists of 0.8 to 1.0% C, 0.3 to 0.5% Mn, 1.5 to 2.0% Cr.[9].

When these rolls are used up to scrap diameter, additional service life can be obtained by sleeving the worn out rolls. The roll outside diameter is reduced by turning to accept a sleeve with 150 mm to 200 mm wall thickness. The forged sleeve bored on a horizontal boring mill is heated to 250°C and then shrunk onto the roll arbour.

In the majority of applications, the sleeved roll out-performs a solid back-up roll because of the improved properties of the forged sleeve material [8]. Differentially heat treated sleeves, 62 Shore with a tensile strength of up to 1580 MPa are used.

CHAPTER III

ROLL CONDITIONS BEFORE MACHINING

3.1 Roll Surface Deterioration, General Aspects

The most important aspect of roll machining is the maintenance of the roll surface quality. This includes both surface finish, the geometric aspect, and the surface integrity which is the physical and metallurgical aspect. Any defect on the roll surface will be transferred to the steel strip being rolled, which could result in product rejection.

There are many factors influencing the deterioration of the surface. Williams and Boxall [10] investigated this in detail. The list below shows these factors for a Hot Strip Mill [10].

Possible mechanisms leading to work roll surface deterioration:

1. Abrasion due to slip between roll surface and plastically deformed strip.
2. Abrasion due to hard iron oxides formed on surface of rolled material.
3. Scale pick-up.
4. Thermal fatigue.
5. Fatigue due to roll separating force.
6. Fatigue due to force between work roll and back-up

roll (which may be increased by the wear patterns of the roll).

7. Hydrostatic forces.

Many of these aformentioned factors are not important since they have little influence on the machining process of rolls.

Cold mill roll deterioration varies considerably from that of hot mills. The absence of high temperature eliminates scale pick-up, thermal fatigue (fire cracking) and the need for roll cooling with highly pressurized water (very erosive).

Roll conditions affecting the machining of heavy rolls will be discussed in more detail in the following sections. These roll conditions might produce machining accuracy errors due to the variations of the cutting forces (discussed in detail in Section 7.1). These variations basically result from the following:

1. Deviation of the geometric roll body shape from its original form, resulting in varying allowances (depth of cut) on the workpiece. The allowances might vary circumferentially as well as longitudinally (along the roll axis).
2. Differences in hardness, both circumferentially and longitudinally.
3. Conditions causing interrupted cutting. Only the most adverse roll conditions shall be discussed irrespective of the roll application, e.g. Hot Mill or Cold Mill.

3.2 Roll Wear Due to Friction and Abrasion

3.2.1 Slabbing Mill Work and Edger Rolls

Work rolls and back-up rolls of all mills must be frequently changed as a result of wear. Work and Edger roll wear is much more severe than back-up roll wear.

The most important factor in work roll wear is the change in velocity of the material within the deformation zone and the directional change of the frictional forces acting on the roll (refer to Section 1.1).

Increasing roll radius R, and the reduction (angle ϕ) results in an increase in frictional forces on the rolls, refer to Equation(5).

The measured amount of wear on a DOFASCO's slabbing mill work roll ranges between 1.5 mm to 2.5 mm per 2 week of service, that of the roughing mill is approximately 0.5 mm to 0.75 mm per day. The wear pattern is nonuniform across the roll body, i.e. concave with maximum wear approximately in the centre.

3.2.2 Finishing Mill Back-up Rolls

The back-up rolls are not exposed to the severity of the deformation zone. Back-up roll wear of differentially hardened rolls (60 to 65 Shore) is typically 0.13 mm per week of service versus 0.5 mm per week for cast steel rolls of 40 to 50 Shore hardness. An increase in roll hardness results in decreasing roll wear.

The wear of hot strip mill work rolls in contrast, is much more severe, despite their high hardness. The cast steel work rolls at DOFASCO are of 50 Shore (Scleroscope C) hardness and the chilled cast iron work rolls are of 78 Shore hardness. Higher roll pressures and increased footage of rolled material in the last stands (#4 Stand to #7 Stand) require rolls of higher hardness, (e.g. 78 Shore) in order to withstand the higher wear rates. A typical amount of wear of 1.8 mm to 2.8 mm per day can be measured. The rolling pressure ranges typically between 150 MPa to 340 MPa compared to 40 MPa to 45 MPa in the slabbing mill application (see Table 4 and 2).

3.2.3 Cold Mill Back-up Rolls

Cold mill back-up rolls are exposed to very similar conditions as hot finishing mill back-up rolls, although the absence of mill scale does reduce roll surface damage. Their hardness and wear rate are approximately the same.

3.3 Roll Wear Patterns

The wear pattern in general is not uniform across the roll body. The 1.5 mm to 2.5 mm wear of the slabbing mill rolls is approximately concave with maximum wear about in the centre.

A stoppage of either work or back-up roll, during the rolling process produces a localized flattening and a localized heat generation which results in a tremendous increase in hardness (10 to 20 Shore). This makes both grinding and turning more difficult. The localized higher hardness can lead to the breakage of the turning tools if speeds and feeds are not adjusted to this condition.

The uneven roll wear, both longitudinally (parallel to the roll axis) as well as circumferentially results in a variation of the machining allowance and therefore the cutting force. The consequence of this variation in the cutting force is a relative deflection between the cutting tool and the roll during the cut. A form error prior to machining, e.g. roll wear, will therefore be re-copied. The degree of re-production depends on the ratio of cutting force stiffness to machine tool stiffness. This ratio in general, is very small for turning and consequently the remaining form error after one cut is negligibly small according to Tlusty and Koenigsberger [36] , [35] . The stiffness ratio in grinding, however, is very much larger. Several passes are required to eliminate form errors. Section 7.1 deals with this in more detail.

3.4 Work Hardening Effect of Rolls

The highly concentrated stresses along the surface contact between back-up and work roll, (refer to Section 2.2

and 2.3) and the cyclic loading of this local area leads to extensive work hardening of the steel rolls, in contrast to iron rolls which do not work harden. As the cycling increases so does the degree of work hardening. Yorke [11] investigated this extensively. Work hardening is particularly of concern with back-up rolls since these are changed very much less frequently than work rolls. Under ideal conditions where both work and back-up rolls are not worn and are provided with the proper crowns, the contact pressure between them is uniform across the roll barrel.

With worn rolls and the thermal growth of the work rolls, however, this contact pressure distribution looses its uniformity. Stone's [12] investigations have established maximum contact pressures of approximately double the average value under ideal conditions, see Figure 3.0. Maximum contact pressure is located near the end of the roll barrel, the minimum value is at the roll centreline. This nonuniformity of roll contact pressures causes a variation of hardness of the roll surface. In-field measurements of roll surface hardness of a DOFASCO hot strip finishing back-up roll which was removed from service showed a range from 45 Shore to 60 Shore hardness, see Figure 3.1. The hardness distribution is similar to the pressure distribution mentioned above. The uneven hardness distribution of the roll results in form errors after machining. The same principles apply as discussed in

Section 3.3.

3.5 Spalling of Rolls

Spalling is a surface failure of the rolls whereby particles of the material are separated from the parent material. The subject was extensively researched through the Roll Research Program of the Iron and Steel Engineers [11] to [14] . There are many causes of spalling, the most common of which are listed below:

1. Work hardening of roll surface.
2. Excessive localized pressure.
3. Sharp temperature gradients.
4. Residual stresses.

These spalls can be very large in size e.g. 150 mm x 100 mm x 50 mm deep on a back-up roll. They are most prevalent at the unworn ends of the worn rolls where the contact pressure between the work roll and back-up roll becomes very high (refer to Figure 3.0). Spalling can occur with all roll materials and rolls, however, it most often occurs on steel back-up rolls due to the work hardening of the roll surface. The frequency of spalling can be very successfully reduced by the removal of the cold worked surface layer, in a lathe or grinder. For this purpose back-up rolls are machined after every third or fourth service period to remove the work hardened material.

This spalling condition results in interrupted cutting during the machining process, which causes form errors. The same principles apply as discussed in Section 3.3.

3.6 Fire Cracking of Rolls

This phenomenon exists only in hot mill applications with both steel and iron work rolls and is caused by excessive thermal stresses and thermal cycling during the rolling. The roll contacts the hot slab (over 1000°C) and the roll surface is rapidly heated and therefore expands. The roll material immediately below the surface is very much cooler and does not expand to the same extent. This produces considerable tensile stresses between the heated surface layer and the cooler layer immediately below. At the completion of each pass there is no more contact with the hot metal. The cooling water cools the roll surface which contracts rapidly and the reverse situation prevails. Due to the alternating stresses caused by the hindered expansion and contraction and the cycling, cracks may appear on the surface of the roll. The orientation of the cracks are axial and due to roll bending are also circumferential. Mill stoppage produces localized cracks running parallel to the roll axis.

Roll manufacturers are limited to a narrow range in the improvement of the resistance against fire cracking. Fire cracking can most effectively be minimized by proper heat control, usually by a well arranged water cooling system.

Typical crack sizes are 1.5 mm wide by 12 mm deep and can grow up to 3 mm wide by 36 mm deep in slabbing mill rolls.

As in Section 3.5, interrupted cutting conditions are present during machining.

CHAPTER IV

PRESENT ROLL MAINTENANCE

Only the maintenance of so called heavy rolls will be discussed here. Heavy rolls include work rolls and vertical edger rolls of the slabbing and roughing mill and all back-up rolls of both hot strip finishing mills and cold mills. All work rolls of these 4 high mills are presently maintained by the use of roll grinding machines. It is not practical to maintain these rolls by turning. The high surface requirements (30AA) of these rolls for both hot and cold rolling and the 93 to 98 Shore "C" hardness of the cold mill work rolls eliminates the possibility of regular maintenance by turning.

4.1 Slabbing and Roughing Mill Rolls

One slabbing mill work roll is ground per week in order to regain the specified cylindricity which was lost due to wear. The diametrical roll reduction approximately equals the amount of wear. One set (two rolls) of edger rolls are turned on an old engine lathe (see Section 4.4) every 26 weeks. The roll diameter is turned down by 25 mm. More roll wear can be tolerated on edger rolls.

The rolls of the intermediate roughing mill are changed more frequently due to the higher shape requirements of the rolled slab as well as the higher wear rate of the rolls, caused by the increase in length of the rolled material. Work rolls are changed and ground every day and approximately 0.8 mm of the roll diameter is removed. One edger roll is turned down approximately 12 mm in diameter every week.

4.2 Back-up Rolls of the Hot Strip Finishing Mill

Back-up rolls of stands 1 to 3 are changed on a bi-weekly basis. Roll wear and shape requirements dictate the grinding of the back-up rolls of the last stands (4 to 7), once a week. With the present roll maintenance method, an average of 1.3 mm reduction of the roll diameter, measured at the deepest wear point is sufficient for normal regrinding of back-up rolls. This reduction suffices to remove almost all of the work hardened material.

DOFASCO's hot mill grinding department, which is organizationally separated from the cold mill operation, initiated recently a new method to minimize the spalling of back-up rolls. As a result of roll research in the industry [12] , [13] , [15] , it was recommended that the cold worked surface layer (refer also to 2.3) of both hot and cold mill rolls be removed before it can become a source of fatigue failure and spalling.

Every fourth regrind, a larger amount, approximately 2.5 mm to 3 mm off the smaller diameter of the roll face, is removed to ensure the complete removal of all work hardened material. This practice resulted in the virtual elimination of roll spalling and therefore substantial savings in roll costs. Due to machining capacity limitations, this program was not applied in the Cold Mill section.

Since the initiation of this new roll maintenance practice in the hot mill roll shop in 1974, the roll life improved from approximately 1.1 million tons of steel rolled per roll to approximately 2.5 million tons rolled per roll in 1979. This represents a roll life extension of 230%. During this time, an increasing amount of low alloy high strength steel of low gauge was rolled which effectively reduces roll life, e.g. average tonnage per roll is lowered. Although roll material changes of the back-up rolls were made during these years, e.g. increasing use of differentially hardened rolls, it is believed by DOFASCO personnel that almost all of the improvement is the result of the new roll maintenance practice. This extension in roll life resulted in an approximate saving in roll replacement cost of $1.5 million per year (based on 1979 production figures).

Approximately two back-up rolls per week require repair to remove spalls, with an average of 13 mm diametrical roll reduction.

4.3 Cold Mill Back-up Rolls

Back-up rolls of most cold mills are changed and ground on a weekly basis. Diametrical roll reductions range from 0.9 mm to 1.3 mm.

4.4 Present Machinery

A total of 17 cylindrical roll grinding machines and two lathes are used in the roll maintenance departments. Both lathes were built in the early 1900's, one is a centre lathe and the other a so called block lathe. The block lathe was a commonly used machine tool in roll turning years ago. It provides only workpiece rotation. The tool is fed into the workpiece usually by a wedge shaped block, hence the name block lathe. Feed parallel to the centre line of the workpiece was simply obtained by re-positioning the tool and block accordingly. This is obviously an old machine tool. The centre lathe lacks the power, stiffness and accuracy requirements. The mechanical condition is extremely poor.

CHAPTER V

PROPOSED ROLL MAINTENANCE, UTILIZING A MODERN ROLL LATHE

The investigation into the application of a roll turning lathe for the maintenance of heavy rolls at DOFASCO was initiated for two reasons:

1. The initiation of the very successful program of spall prevention which virtually eliminated all the spalling of hot strip mill back-up rolls by the removal of the work hardened surface. This practice requires extra heavy metal removal off the roll body.
2. The elimination of the requirement to grind the roll surface for all hot strip mill back-up rolls.

Since slabbing and roughing mill rolls as well as hot strip mill back-up rolls do not require ground roll surfaces and the spall prevention program requires extra heavy cutting, a more efficient metal removal process than grinding is desirable. Such a process is turning, however, since the roll materials to be machined are relatively hard and the surfaces not uniform (e.g. spalls, fire cracks) a closer investigation into machining time is necessary to determine cost savings. This study was conducted by the author, however, only the conclusions of this internal DOFASCO report will be discussed in Sections 5.1 to 5.3.

5.1 Hot Mill Rolls

The proposed new lathe is to be used for the following maintenance functions:

1. The regular dressing of back-up rolls, removing roughly 1.3 mm off the roll diameter.
2. Extra heavy cutting (2.5 mm off diameter) to remove the work hardened surface of back-up rolls in order to prevent spalling, usually every fourth dressing cycle.
3. The regular dressing of all slabbing and roughing mill rolls.
4. The repair of all rolls - spalled, fire cracked and various other damage - all requiring extensive machining.

All hot mill rolls can be finish machined by turning, with the exception of the work rolls of the finishing stands which require grinding.

A machining time comparison of grinding versus turning of hot strip mill rolls is given below [author's DOFASCO report]:

Rolls Machined	Roll Diameter Reduction mm	Grinding Time hours	Turning Time hours
Back-up Rolls, Regular Maintenance	1.3	4	2
Back-up Rolls, Spall Reduction	2.5	6	2
Back-up Rolls, Repair	12	20	4
Work Rolls, Repair	3.8	6	1.5 + 1 hour Grinding

The higher metal removal capability of a lathe is very evident. Grinding times are actual recorded production figures, whereas the turning time is based on calculations. The author concludes in his report that an increase of at least 220% can be anticipated by applying one new lathe versus the existing method of using the cylindrical roll grinders and an existing lathe.

5.2 Cold Mill

Roll surface requirements in cold mill applications are higher than those of hot mills. The surface finish must not be rougher than 0.8 μm. Since this surface quality is difficult to obtain by turning, all rolls have to be finish ground after turning. The bulk of the material to be removed from the roll body will be done by turning (e.g. 2.2 mm out of 2.4 mm). A very small amount will be removed by grinding, just enough to obtain the required surface quality.

The economic justification for a lathe was based on the maintenance of back-up rolls only, however turning would be justifiable for the repair of badly damaged work rolls. The increase in productivity in maintaining cold mill back-up rolls was calculated to be 56%. This was generated by an internal DOFASCO report by the author and will not be substantiated here. This relatively low increase in productivity, when compared to the 220% of the hot mill rolls, reflects the need for grinding all rolls after turning.

5.3 Cost Savings

The acquisition of a $1 million roll turning lathe for the maintenance of DOFASCO's hot mill rolls and cold mill back-up rolls results in substantial savings. The author's investigation, reported in an internal DOFASCO report, concluded that annual machining time can be reduced by approximately 8000 man-hours, based on present production levels. The installation of a lathe, in addition to above savings, makes approximately 14,000 hours of grinding time per year available. This allows the scrapping of two outdated grinders which otherwise needed to be replaced. The capital cost for the replacement of the grinding machines can therefore be saved. The cost of a fully equipped 1500 mm x 6200 mm cylindrical roll grinder is approximately $1.2 million. Installation cost can be very expensive depending on the soil condition of the installation site and ranges typically from

$100,000 to $300,000.

CHAPTER VI

ROLL LATHE SPECIFICATIONS

6.1 Physical Size

The physical size of a roll lathe depends on the largest roll to be machined. DOFASCO's largest back-up roll in service at present, is that of the 5 Stand 72" Cold Mill, with a maximum diameter of 1537 mm and a 4010 mm roll length. The longest roll is used on the 88" 2 Hi Slabbing Mill with a length of 5750 mm (refer to Table 7).

A typical back-up roll of the hot strip finishing mill is shown on Figure 6.0.

A centre lathe of 6500 mm between centers is required. Extra bed length is added to the maximum roll length to accomodate an easy loading into the centers of the lathe by overhead cranes. This is necessary to prevent damage to the machine tool through loading. The maximum load between centers is 360 kN. The swing over the cross slide must be a minimum of 1540 mm and preferably larger.

6.2 Tooling Aspects

In order to determine speeds and feeds, it is necessary to look at the tooling first. An investigation into tool life and economic cutting conditions is made in Section

6.2.4. This can be compared to practically achieved cutting values and cutting tool materials presently applied in the industry (see Section 6.2.1 and 6.3). Tungsten carbides, aluminum oxides and other recently developed tool materials are being used today. In order to utilize these tool materials to their fullest extent, in particular the more exotic ones, the machine tool, tool holder and workpiece must be extremely rigid [18]. This is even more important when the cutting is interrupted due to the presence of fire cracks or spalls.

6.2.1 Tool Materials

In general, an evaluation of cutting tools is very difficult to make. Published test results vary tremendously from manufacturer to manufacturer. Often no information on grain sizes or alloying contents are made available. It is therefore very difficult to draw a clear line of application for the use of one tool material or another.

The most reliable evaluation is to be achieved by performing cutting tests with the specific workpiece and the actual machine tool in question.

The desired properties of cutting tool materials are:

1. High hardness and wear resistance.
2. High mechanical strength.
3. Preservation of the above properties at elevated temperatures.

4. Resistance to diffusion and adhesion.

5. High thermal shock resistance.

An ideal tool material would combine all these properties, however, since this is not practically possible, compromises must be made. One cannot obtain a high hardness combined with a high degree of toughness.

Tool materials in general have little ductility, their tensile and compressive strength is quite different, in contrast to ordinary steels where the compressive and tensile strength is about the same.

6.2.1.1 Cemented Tungsten Carbides

6.2.1.1.1 Cast Iron Cutting Grades

The basic tungsten carbides were developed by Krupp in 1926 and are commonly known as "straight carbides".

Under the industry code [19] they are listed as C-1 to C-4 grades and are applied for cutting cast iron, nonferrous and nonmetalic materials. Detailed information concerning the characteristics of these carbides are readily available, refer also to [18],[20],[21].

The microstructure consists of two primary constituents, tungsten carbide and cobalt. The cobalt is the binder and is relatively soft and ductile, providing the tough component of this composite material. The carbide grades vary chiefly in cobalt content and grain size. The strength and hardness of the cemented carbides are controlled by varying the amount of binder metal. The lower the cobalt content, the harder and more brittle is the composite structure, refer to Table 8.

The parameter used to measure the strength of the tool material is the Transverse Rupture Strength. This parameter is generally measured by means of a bending test. The maximum value of the maximum tensile stress at fracture load is the Transverse Rupture Strength (TRS). Tlusty [22] gives a more detailed account of this.

A very important characteristic of the cast iron grade carbides is the diffusion wear if used for cutting steel. At elevated cutting temperatures diffusion reaction between the carbide tool and the chip of the work material greatly contributes to the tool wear rate. This wear pattern which occurs on the rake face of the tool is called crater wear.

The diffusion wear mechanism [23] can be explained simply as an exchange of free carbon from the carbide tool to the chip of the work material. The straight carbide lends itself to the machining of cast iron due to the relatively high amount of carbon of the cast iron . The diffusion reaction caused by the carbon exchange is therefore minimized when cutting cast iron. The same straight carbide grade, when cutting steel materials, would develop severe cratering because of the diffusion of carbon into the chip, which contains a relatively low amount of carbon.

Despite extensive new developments in the cutting tool field, the straight carbide grades are still extensively used in industry. They remain the work-horse in the machining of cast iron rolls.

6.2.1.1.2 Steel Cutting Grades

Cratering tool wear on the rake face has been most serious in the case of machining steels with the so-called "straight" carbide tools.

The addition of Titanium and Tantalum carbides to the basic carbide structure, tungsten carbide and cobalt, prevents cratering when machining steels [21] .

The titanium carbide was found to be the essential additive to impart crater resistance. It provides the stability to prevent the diffusion of the free carbon from the tool material into the chip and this makes it suitable for the machining of steels.

The C-5 to C-8 grades are the steel cutting grades, having the titanium and tantalum carbide addition (refer to Table 8). Toughness decreases, hardness and therefore surface speed capability increases in going from a C-5 to C-8 material grade.

6.2.1.2 Micrograin Cemented Carbides

Patts [24] points out that micrograin cemented carbide grades, when compared to conventional carbides, display a more desirable strength-hardness relationship, and an improved hot hardness. These micrograin cemented carbides are basically nothing more than a refined version of the conventional carbide.

Commercial grades of WC-Co have a range in average particle size from 0.1 μm to just less then 0.025 μm. Typical micrograin sizes are around 0.025 μm to 0.05 μm [24] .

When selecting a tougher cutting tool of the previously discussed cemented tungsten carbide tool materials, the hardness was decreased and strength was increased, either by increasing the cobalt content or by increasing the grain size. If a more wear-resistant grade was needed, a compromise had to be made by increasing the hardness and decreasing strength. Tool selection required a consistant trade-off of strength versus hardness. With the micrograin carbides it is possible to increase hardness with an increase of strength. This is the outstanding characteristic of micrograin carbides.

Figure 6.2 shows the hardness as a function of cobalt content for conventional carbides with 0.1 μm and 0.05 μm average particle size, as well as micrograin alloys with a particle size of less than 0.02 μm. The micrograin material is harder than a 0.05 μm average particle size cemented carbide, which in turn is harder than a 0.1 μm carbide. Similar graphs can be used to show the relationship between the transverse rupture strength versus cobalt content and average particle size.

Figure 6.1 shows the previously mentioned relationship between transverse rupture strength versus hardness. Both micrograin and conventional grade of carbide show decreasing transverse rupture strength with increasing hardness, however, with the micrograin carbide, this occurs at a distinctly higher level.

The primary benefit of micrograin carbides according to Patts [24] is their higher transverse rupture strength for any given hardness level. This makes them more suitable for the cutting of spalled rolls, where the cutting process is interrupted by the local break-out of the roll material.

Some micrograined carbides, having no TiC additives have poor crater resistance. This makes them unsuitable for machining steel rolls.

6.2.1.3 Ceramics

Ceramics are made from aluminum oxide or contain a high percentage of aluminum oxide.

The following alloying elements are used:

1. Metal carbides such as MoC, WC, TiC.
2. Oxides such as silicon-oxide and metal-oxide.
3. Pure metals such as Mo, W and V.

On the market there are mainly two groups available, ceramics containing aluminum oxide (Al_2O_3) only or with very small amounts of alloying elements, and cermets which contain a larger amount of metal carbides.

There are several physical characteristics which are distinctive to ceramic tool materials [25], [26], [27]. One of these is the low heat conductivity of .03 versus .13 cal/sec. cm$^{\circ}$C of WC at 800°C. For a given heat flux the temperature gradients in the tool will be larger for materials with a low conductivity. This temperature differential becomes particularly critical in the cooling process of the ceramic material. The outer part of the insert shrinks and tensile stresses are created. These thermal stresses are especially serious in interrupted cutting, such as in [illegible]ing. The machining of heat cracked rolls cannot be interpreted as an interrupted cutting process in this sense, since the cooling cycle is extremely short. This low heat conductivity makes ceramics easily susceptible to heat cracking.

Binns [28] and Gettelman [29] claimed that the high hardness of the material, which is also maintained at high temperatures, lends itself for machining of very hard materials such as chilled iron and hardened steel rolls (up to 90 Shore). The tool, however, must be rigidly supported. Prior to ceramics, grinding was the only process capable of machining steel and cast iron this hard. The high hardness and therefore the lower transverse rupture strength (Table 9), combined with the sensitivity to thermal shock limits the usage of ceramics somewhat if standard lathes and tool holders are used. Because of the low strength of ceramics, the load per unit length of cutting edge must be small (refer to Section 6.2.2). Mechanical stresses within the cutting tool are minimized by using rigid machine tools and tooling. Under these conditions it is possible to use ceramics for interrupted cutting such as is the case in fire cracked rolls [28], [30]. Milling operations with ceramics are not yet practically possible.

The chemical inertness of ceramics prevents diffusion occurring with most materials and explains the high resistance to wear, expecially crater wear.

Ceramics achieve a longer tool life compared to WC. The economical cutting speed is 1.5 to 2.5 as high as with comparable carbides (Figure 6.3).

Today, the use of ceramics is mainly limited to finishing cuts, high speed and low feeds, for the machining of cast iron and high strength, high hardness steels. The turning of DOFASCO's back-up rolls is a suitable application for ceramic tools.

6.2.1.4 Titanium Carbides

Titanium carbides, TiC, can replace WC in some applications on the basis of much higher resistance to flank wear and cratering [31]. When compared to WC in the same application, the lower wear characteristics of TiC results in longer tool life or increased cutting speeds for the same tool life (see Figure 6.4). As a result of a higher flank wear resistance a longer lasting surface finish and accurate size control of the machined parts can be achieved.

Titanium carbide produces its own cutting edge protection shield by the formation of oxides (Ti, Mo) which act as a dry film cutting lubricant. As a result both edge build-up and tool force are decreased and crater wear is very low.

When compared to ceramics, TiC has an inferior abrasion resistance. It also has not been too successful with high temperature and super alloyed steels, for many non-ferrous steels and some cast irons. In general, for those applications in the C-1 to C-4 category, one does not find cemented titanium carbides to be suitable.

6.2.1.5 Titanium Coated Carbides

A thin (0.005 mm) coating of TiC is metallurgically bonded to a suitable carbide substrate. Such a composite carbide cutting tool material can perform a broad range of machining operations exhibiting the toughness of a roughing grade and the wear resistance of a finishing grade.

The characteristics of TiC coated tips are similar to that of a pure TiC [32] . In comparison to WC of similar strength they offer decreased friction leading to thinner chip, cooler tool, lower cutting temperature, less power to remove the same amount of metal, reduction of crater wear, and longer lasting surface finish. For machining common grades of steel this means that an increased tool life can be achieved using the same cutting data. Increased production rates can be achieved by increasing cutting speeds with TiC coated inserts (Figure 6.4).

The performance of TiC coated carbides lies between WC and ceramics. It is therefore suitable for general purpose and finishing machining of steels and most cast irons. It is not suitable for heavy duty machining and the machining of high temperature alloys.

6.2.1.6 Cubic Boron Nitrides (CBN)

This relatively new cutting tool is made from cubic boron nitrides (CBN). The particles are sintered into a highly dense layer (0.5 mm to 0.8 mm) on a cemented carbide pad. The WC provides the base for rigidity and toughness.

CBN tools are more expensive than others and can therefore be economically resharpened.

The outstanding characteristics of CBN and other similar materials (nitride TiN, silicide WSi_2) is the high temperature strength, non-reactivity, the extreme hardness and abrasion resistance, the very low tensile rupture strength and their high costs.

The CBN was mainly developed for difficult to machine alloys. The nickel base alloys for example contain a significant amount of metal carbides that are highly abrasive.

Other materials are cobalt-base super alloys and highly abrasive silicon-aluminum alloys.

WC cannot sustain temperatures higher than 700°C because of the chemical reactivity and tool oxidation, Borazon on the other hand is good up to 1200°C.

Cutting tests were made by Herzog [32] at speeds over 900 m/min, when machining silicon-aluminum alloys and metal removal rates of more than 5 times those of carbide tools were claimed.

Because of the peculiar chip formation and cutting process which is done under continuous cooling, it is not possible to generate a square shoulder. Due to the tool's brittle nature, its tolerance for interrupted cuts such as fire cracked rolls or scale cuts is extremely low.

Cubic Boron Nitrides as well as all other brittle cutting tools (ceramics) require an increase in systems rigidity. Bruins and Dräger [18] estimated that CBN tools require at least twice the rigidity as their carbide equivalents.

Although many claims [33], [29] are being made in favour of CBN tools, their practical application is still very limited.

6.2.2 Tool Geometry

Tool angles influence the cutting forces and power requirements, tool wear and tool life. They also influence the dynamic characteristics of the workpiece-tool - machine tool system.

All cutting edge angles are shown on Figure 6.5. The use of a large negative rank angle is always necessary to cut materials which are difficult to machine. For the machining of rolls the rake angle ranges from -5^{o} to as much as -30^{o}, depending both on the workpiece and tool material, [26] , [27] , [28].

The relief angle γ is larger but does not vary drastically from that of conventional steel machining.

The most drastic change for the machining of rolls has to be made with the approach angle $\mathcal{X}$.

In cutting hard materials, as is the case with rolls, the specific cutting edge load of the tool material is very high [18] . This specific cutting edge load is the load per millimeter of cutting edge length during the cut and is expressed by:

$$p_s = \frac{F_v}{b} \qquad (13)$$

whereby F_v is the force component in the direction of the cutting speed (see Figure 6.11), and b is the chip length. Figure 6.6 shows the relationship between chip length b and chip thickness h and the approach angle $\mathcal{X}$. This is expressed in

$$h = s \times \sin \mathcal{X} \qquad (14)$$

Chip load on the tool decreased by decreasing the approach angle $\varkappa$.

The very high specific cutting force of roll materials, see Section 6.6.1 and Figure 6.12, requires a reduction of the specific cutting edge load if the tool material is to be fully utilized to maximize metal removal rates. This is achieved by reducing the approach angle $\varkappa$. The application of ceramics as a cutting tool (when compared to carbides) requires a reduction in the specific cutting edge load. This is due to the high hardness and low transverse rupture strength of ceramics (see Table 9). A decrease in the approach angle $\varkappa$ in general leads to a decrease in the stability of the machining system, (e.g. chatter will occur). This has been thoroughly investigated by Tlusty [35] , [36]. Chatter is most easily obtained by plunge cutting, with $\varkappa = 0^{\circ}$. Stability against chatter increases greatly with an approach angle of 90°.

6.2.3 Typical Tooling Designs

A similar tool holder as that on Figure 6.8 was used by Binns [34] to remove 165 mm from the diameter of a roll at a hardness of Rc 35 in a single pass. A feed as large as 2.2 mm per revolution and a cutting speed of 45 to 52 m/min was used with both carbide and ceramic cutting tool inserts.

A suitable tool for finish turning (e.g. removal of 1.3 mm to 3 mm in diameter as required in roll turning at

DOFASCO) is shown on Figure 6.9.

Button type tools are used mainly for finishing operations requiring good surface finish.

With the tool shown on Figure 6.7 a surface roughness of 0.8 μm was achieved by Binns [34].

6.2.4 Tool Life Optimization

6.2.4.1 Tool Life Optimization Considering Machining Time

The cutting process produces wear on the tools. The wear takes place mainly on the rake face (called crater wear) and on the clearance face of the cutting tool. The latter is called flank wear and is the most valid criteria for tool wear and tool life evaluations.

The basic tool life equation is:

$$v_c{}^p s^q \; T = C_T \text{ (constant)} \tag{15}$$

whereby the speed effect on tool life T is more significant than that of the feed. Values p range typically from 2 to 5 and q from 1 to 4 [20] and $p > q$.

Optimizing tool wear to yield maximum production rates at minimum costs leads to the selection of required speed and feed rates. Given the length of roll barrel "L" and the depth of cut "a", the machining time "t_m" can be calculated [20] :

$$t_{m/part} = \frac{L_m}{s\ n} = \frac{L_m \pi d}{s\ v_c} = \frac{A_s}{s\ v_c} \qquad (16)$$

the tool change time t_{tch} per part is:

$$t_{tch/part} = \frac{t_{tch}}{\#\text{of parts}} = \frac{t_{tch}}{\frac{T}{t_m}} = t_{tch}\frac{t_m}{T}$$

$$t_{tch/part} = t_{tch}\frac{A_s v_c^{p} s^{q}}{s v_c C_T} \qquad (17)$$

Total time t_{ToT} is

$$t_{ToT/part} = t_{m/part} + t_{tch/part}$$

$$t_{ToT/part} = \frac{A_s}{s v_c}\left(1 + t_{tch}\frac{v_c^{p} s^{q}}{C_T}\right) \qquad (18)$$

The total machining time is to be minimized. The partial derivatives of Equation (18) yield:

(a) $$\frac{\delta t_{ToT}}{v_c} = 0 = \frac{A_s}{s v_c^2}\left[(p-1)\frac{t_{tch}}{C_T} v_c^{p} s^{q} - 1\right]$$

(b) $$\frac{\delta t_{ToT}}{s} = 0 = \frac{A_s}{s^2 v_c}\left[(q-1)\frac{t_{tch}}{C_T} v_c^{p} s^{q} - 1\right]$$

(a_1) $$(p-1)\frac{t_{tch}}{C_T} v_c^{p}\ s^{q} = 1 \qquad (19)$$

(b_1) $$(q-1)\frac{t_{tch}}{C_T} v_c^{p}\ s^{q} = 1 \qquad (20)$$

All practical values of p and q are: q>1 and p>2. This means that the $\frac{\delta t_{ToT}}{\delta v_c}$ curve is the minimum curve in a speed - feed diagram.

Since the tool life T equals:

$$T = \frac{C_T}{v_c^{p} s^{q}} \text{ from Equation (15),}$$

Equation (18) leads to the optimum tool life T_{opt}:

$$T_{opt} = t_{tch} \; (p-1). \qquad (21)$$

6.2.4.2 Tool Life Optimization Considering Costs

The cutting tool related costs are [20] :

$$C_{Tool} = t_{tch} \; r_m + C_{CUT\ EDGE} \qquad (22)$$

whereby r = machine rate $/minute. The machine rate "r_m" includes all costs such as wages and total overhead. $C_{CUT\ EDGE}$ = the cost per cutting edge of the throw - away cutting tip.

Total cost C_{ToT} is:

$$C_{ToT} = t_m \; r_m + C_{Tool} \; \frac{t_m}{T} \qquad (23)$$

In order to minimize the total cost C_{ToT} the machining time t_m must be minimized. This is done by maximizing the metal removal rate which in turn means the maximization of the cutting feed.

An increase of the cutting speed also results in the desired increase in the metal removal rate but leads to a reduction of tool life. An increase in feed does not reduce tool life to the same extent as an increase in speed.

The same mathematical procedure as in the previous Section 6.2.4.1 leads to the optimum tool life T_{opt} of Equation (23) which includes the total cost aspect and is:

$$T_{opt} = \frac{C_{Tool}\ (p-1)}{r_m} \tag{24}$$

6.2.4.3 Example - Roll Turning

For machining a DOFASCO back-up roll of the hot strip finishing mill with an average hardness of 58 Shore (Scleroscope C) the following data are given by Feldmühle [26] :

Tool Material: Ceramics with 30% Titanium Carbide		
Chip Thickness	h :	0.10 mm
Feed	s :	0.4 mm/r
Depth of Cut	a :	2 mm
Approach Angle	χ :	15^{o}
Tool Nose Radius	R_T:	1.27 mm
Tool Wear Criteria, Flank Wear	:	0.2 mm

From the tool life - cutting velocity diagram for above data a value of $p = 5.7$ was obtained [26] .

The following data are approximate and might represent roll maintenance operations in the steel industry in general:

Tool Change Time	t_{tch} =	2 minutes
Machine Rate	r_m =	\$0.82/minute

Cost of Cutting Edge $C_{CUT\ EDGE} = \frac{\$10 \text{ per tip}}{4 \text{ edges}}$

$= \$2.50$ / edge.

This yields:

Optimum Tool Life, Considering Minimum Cutting Time:

$$T_{opt} = t_{tch}\ (p-1) = 9.4 \text{ minutes}$$

Optimum Tool Life, Considering Minimum Costs:

$$T_{opt} = \frac{C_{Tool}\,(p-1)}{r_m} = 23 \text{ minutes}$$

This corresponds to a cutting speed of 65 m/min and for the latter, a speed of 56 m/min, obtained from Feldmühle's [26] tool life curve. Tool life is based on 0.2 mm flank wear.

There is a substantial difference in tool life when considering minimum cutting time versus minimum costs. Machining costs are the main concern, therefore, the cutting speed selected is 56 m/min for minimum costs.

6.3 Actual Cutting Performances

Materials which were and perhaps are still in many instances considered impossible to cut, are being machined by single point cutting tools today. Some of these actual cutting performances are listed below:

Example 1 (from Binns [34])

Workpiece: 990 mm dia. x 2800 mm length of cut.

Material: Cast Steel, 0.8% carbon and high nickel alloy at RC42 (56 Shore)

Cutter: Ceramics G.E. 0-30 with $\gamma = 10^{\circ}$ clearance, $\alpha = -18^{\circ}$ negative top rake, and 22.2 mm long cutting edge at approach angle $\varkappa = 0^{\circ}$

Depth of cut: 0.25 mm

Feed: 19 mm per revolution or 838 mm per minute

Cutting speed: 137 m/min (44 r/min)

Rate of metal removal: 664 cm^3/min

Power required: 19 kW at the cutter

Energy rate of cutting: 35 cm^3 per minute per kW

Surface finish: Less than 0.76 μm

Cutter life: 20 minutes per index

Note: Surface finish was the limiting factor, and as measured, does not include wave pattern which is a function of the accuracy of setting the cutter to exactly $\varkappa = 0^{\circ}$ approach angle. With care in cutter grinding and setting, the waviness can be held to .0025 mm. With multiple inserts, the depth of cut can be increased to 1.5 mm on the radius, and power in the cut to 112kW (see Figure 6.7).

Time to cut the 2800 mm length is only 3 minutes for either conditions.

Example 2 (from Binns [34])

Workpiece: 330 mm dia. x 711 mm long cut from "as cast" condition, chilled alloy iron, (77 Shore "C")

Tool: Ceramics, $\gamma = 5^{\circ}$ clearance, $\alpha = -15^{\circ}$ negative top rake, and set at approach angle $\varkappa = 20^{\circ}$

Depth of cut: 4.8 mm - average

Feed: 1.14 mm per rev. or 40 mm per minute for 0.4 mm chip thickness

Cutting speed: 36.6 m/min (35 r/min)

Cutter life: 60 minutes per index

Accumulated results of practically achieved cutting data are shown in Table 10.

Example 3, using cubic boron nitride tools (from Herzog [33]).

(A) Workpiece: 635 mm dia. x 2286 mm rolls

Material: 52100 with 64 RC hardness (90 Shore)

Cutting speed: 91 m/min

Feed: 0.46 mm/r

Depth of cut: 1.27 mm

Tool angles: Approach angle $\varkappa = 45^{\circ}$, rake angle $\alpha = -5^{\circ}$, clearance angle $\gamma = 5^{\circ}$.

Tool life: Approximately 80 minutes at 0.5 mm flank wear

(B) Workpiece: Hot strip mill roll, 736 mm dia. x 1524 mm length

Material: Chilled iron, hardness 58 RC (80 Shore)

Cutting speed: 137 m/min

Feed: 0.25 mm/r

Depth of cut: 5.1 mm

Tool angles: Approach angle $\varkappa = 45^{\circ}$, rake angle

$\alpha = -5^{\circ}$, clearance angle $\gamma = 5^{\circ}$

These production figures are astounding and rather hard to accept, yet, they have been proven in several different branches of the roll industry. They are realistic if the machine tools used are of a very rigid design.

6.4 Surface Finish - Required Feed Range

Surface requirements for Hot Mill back-up rolls are 3.2 μm or of better quality. It is not known whether work rolls for finishing stands can be economically finish machined by turning. This remains to be investigated. The lathe however, should be purchased with the capability to do this as well. Finish requirements for work rolls is 1.6 μm. With the use of a 25.4 mm diameter button tool tip and 1.6 μm surface finish a feed rate of 0.86 mm per revolution is required (see Figure 6.10). For better surface quality finishing cuts, the approach angle χ of a square tool tip could be reduced to zero, as shown on Figure 6.7. This represents a button tool with an infinitly large radius R. In Section 6.3, Example 1, a feed rate of 19 mm/r was used for this purpose. According to Table 10, a feed rate range from 0.25 mm/r to 2.3 mm/r is needed for semi-finishing and finishing operations. Total range for the new machine is therefore from 0.25 mm/r to 19 mm/r. The machine should be equipped with at least the range specified above, preferably having a wider feed range to allow for new tooling developments and operating practices in the future.

A rapid traverse feed is also needed.

6.5 Requirements for Cutting Speeds

The range of workpiece diameter is 1537 mm maximum for the largest back-up roll to approximately 711 mm for the smallest work roll diameter (Hot mill finishing mill). Surface speeds, as per Table 10, range from 27 m/min to 180 m/min. Required RPM range is therefore:

$$\text{RPM maximum} = \frac{v_{Max}\ 12}{d_{Min}\ \pi} = \frac{180 \times 10^3}{711 \times \pi} = 81 \text{ RPM}$$

$$\text{RPM minimum} = \frac{v_{Min}\ 12}{d_{Max}\ \pi} = \frac{27 \times 10^3}{1537 \times \pi} = 5.6 \text{ RPM}$$

6.6 Cutting Forces and Power and Their Relationship to Practical Variables

Power consumption and forces generated by the cutting process affect the size and design of the required machine tool. The forces directly affect the accuracy of the workpiece due to the deflections of the workpiece and machine tool components which are produced by these forces.

6.6.1 Forces

Tlusty [36] directed extensive investigations concerning cutting forces. The force component F_v, (see Figure 6.11), in the direction of cutting speed, is the most important. It determines the power consumed in cutting. The remaining two force components do little or no work, however, they do produce deflections in workpiece and machine tool.

Force F_v does not vary much with the cutting velocity v_c, especially in the useful range above 45 m/min [36] .

F_v does depend on the tool angle, especially the rake angle, however, there is not much choice in rake angle for a particular combination of workpiece and tool materials because of the strong influence on tool life.

With few exceptions, forces are practically independent of tool materials. Thus for F_v we have to deal with effects of the dimensional cut (see Figure 6.6) and the workpiece material (see Table 6).

F_v is generally expressed as:

$$F_v = C\ b\ h\ h^{-c} \qquad (25)$$

rearranged:

$$F_v = C\ h^{-c}\ h\ b = F_s\ A$$

whereby the specific force:

$$F_s = C\ h^{-c}\ (N/mm^2) \qquad (26)$$

and "c" is a material constant.

A specific force diagram was plotted on Figure 6.12 from values given in references [36] , [37] , [38] and [39].

As a rough and general rule, forces and power consumption increase with increasing hardness.

The microstructure of a particular material has usually very little effect on the forces or power consumption, except as it affects the hardness of the material.

The cutting force components F_v, F_f, F_r and their ratios $F_v : F_f : F_r$ are influenced by the cutting tool angles [40] . For a given chip cross section (a x s) a decrease in the approach angle "χ" results in a decreasing chip thickness "h" and an increasing chip width "b" (see Figure 6.6). This means that the specific cutting force F_s will increase (see Figure 6.12), and with it the main cutting force component F_v. The radial component F_r increases while the feed force component F_f decreases.

6.6.2 Power Requirements

Maximum power requirements for a universal machine tool used for machining of ferrous materials is determined by the low carbon, low strength steel [36] . Strength or hardness of a material to be cut has a greater effect on tool life than on cutting force. With increasing strength or hardness the cutting speed must be decreased in a greater ratio than the force increases, for a given size of cut. Since power is the product of force and cutting speed, the initial statement has therefore been substantiated.

Whether the relationships of these above mentioned factors apply in the same way to the more exotic roll materials is not known and the maximum power requirements has therefore been calculated for all different roll materials.

One can observe (Table 6) that there does not always exist a direct relationship between hardness and material strength in rolls. An empirical relationship between the two factors was developed by Kronenberg [40] and applies for most metals commonly machined.

The various surface conditions (fire cracks, spalls etc...) of different rolls, (e.g. slabbing mill rolls versus back-up rolls), requires a compensation of the cutting data. For the calculation of maximum power requirements a maximum depth of cut of 3 mm as per recommended procedure to prevent spalling (refer to Section 3.5), is used as a basic dimension, common to all roll materials.

The net power P_c required at the cutting tool is simply calculated as:

$$P_c = F_v v_\alpha \qquad (27)$$

whereby F_v can be expressed as:

$$F_v = A\, F_s = b\, h\, F_s$$

refer to Equations (25) and (26). This yields:

$$P_c \doteq \frac{b\, h\, F_s\, v_c}{60} 10^3 \quad \text{(kW)} \qquad (28)$$

Maximum values of feed rates and cutting speeds above those normally used are selected in order to yield maximum power requirements, (refer to Table 10). The machine tool must be equipped such that it can use these maximum feeds and speeds. It is unjustified for present use, however, new tooling developments will surely be achieved during the life time of the machine tool e.g. more power will be required to accommodate these new tools.

Maximum power at the tool is: $P_c = 46.2$ kW (from Table 11). This power must be available at and above a certain speed, called n_{Lim}, (refer to Figure 6.13). Section 6.6.3 deals with n_{Lim} more extensively.

The required motor power is:

$$P_{mot} = \frac{P_{c\ max}}{\eta} \tag{29}$$

The coefficient of machine tool efficiency η is generally at least 0.8 or better for a typical modern heavy lathe according to Bruins and Dräger [18].

$$P_{mot} = \frac{46.2}{0.8} = 57.8 \text{ kW}$$

A motor of 60 kW would therefore be amply sufficient.

6.6.3 Torque Requirements

The other parameter besides power that determines the loading capability of the spindle drive is the maximum torque T_{max}.

$$T_{max} = F_{v\ max} \frac{d_{max}}{2} \tag{30}$$

The maximum cutting force $F_{v\ max}$, determines the load and design of the structural components such as the bed and the carriage.

The relationship between power, speed and torque needs further investigation. For many turning operations at high speeds, generally used for smaller diameters and finishing cuts, the torque requirement is low. A low cutting speed is used for turning large diameters which requires a large torque but the low speed makes the necessity for full power unnecessary. For these reasons, the drive system of most lathes is designed for constant power for high speeds and constant torque for the low speed range [40] . A certain speed n_{Lim} exists within the speed range at which the two limitations T_{Max} and P_{Max} coincide. Figure 6.13 shows this relationship for a typical roll turning lathe. This lathe is equipped with a D.C. drive motor and four manually controlled speed ranges. Below n_{Lim} the torque is constant at the level T_{Max} and the power decreases proportionally with decreasing speed. P_{Max} is kept constant above n_{Lim} and the torque decreases inversely proportional to the speed.

The maximum torque requirement is calculated for maintenance of heavily damaged rolls, (e.g. removal of spalls) and is calculated as follows:

$$T_{Max} = \frac{d_{Max}}{2} \cdot F_{s\ Max}\ s\ a = 69,500\ \text{Nm}$$

For this calculation a 38 mm depth of cut and 0.508 mm/r feed is selected. The largest roll diameter of 1537 mm coincides with the roll material having the highest specific cutting force F_s at 4,688 N/mm^2, see Tables 7 and 11.

The speed n_{Lim} at which the condition of maximum torque and maximum power exists, can be calculated as below (see power, torque versus speed diagram of Figure 6.13):

$$n_{Lim} = \frac{P_{Max}}{T_{Max}\ 2\pi} = 6.4 \text{ r/min} \qquad (31)$$

Figure 6.13 was obtained from Maschinenfabrik Deutschland (MFD) [43] , a very reputable roll lathe manufacturer and matches the requirements of torque, power and cutting speeds very closely.

6.6.4 Machining Capability Utilizing 60kW Drive

With cutting data acceptable today, the depth of cut is to be calculated utilizing 60kW. The roll material chosen is that of the Hot Mill finishing stands, material group 2 (cast steel) with an approach angle $\chi = 45^\circ$, semi-finished cutting, no skin, clean surface, 60 m/min cutting speed and 0.50 mm/r feed. Specific cutting force from Figure 6.12 at:

$$h_{average} = 0.353 \text{ mm},$$

$$F_s = 1800 \text{ N/mm}^2 , \eta = 0.9$$

$$a_{max} = \frac{P_{mot}\,\eta}{F_s\, v_c\, s} =$$

approximately 60 mm depth of cut.

Metal removal rate;

$$Q = A\, v_c = 1800\ cm^3/min$$

or

900 kg/hour

This high metal removal rate necessitates an efficient removal system of the cutting chips.

CHAPTER VII

DESIGN CHARACTERISTICS OF A ROLL LATHE

The design of the constructural elements of a roll lathe are in principle the same as for a standard engine lathe. There are however specific differences which will be discussed in the following sections.

Machine tool reliability, obtainable accuracy and performance can be assured by the following means:

- Purchase a well proven lathe model from a reputable manufacturer.
- Write stringent specifications and acceptance tests, including accuracy, performance, life and reliability tests.
- Scrutinize individual design elements of different lathe manufacturers, analyze and compare.

A typical roll lathe is shown on Figure 7.0.

7.1 Structural Deformations Caused by Cutting Forces

The proposal for roll maintenance was to utilize a roll lathe and machine across the roll body with a single cut, unless extensive repair work is required. It has to be determined whether the obtainable accuracy of the finished turned roll will be sufficient under this condition. The question has to be answered as to whether structural deformations caused by the variable cutting forces and variable machine tool stiffness will introduce large, unacceptable errors.

Extensive investigation concerning cutting force deformations were undertaken by Tlusty and Koenigsberger [36] [35] , [41] . The authors state that there are basically two reasons for the variation in the relative deflection between the workpiece and the tool.

1. The cutting force varies due to the variable depth of cut and the variable surface conditions of the roll. These conditions were discussed in detail in CHAPTER III. An uneven pattern of roll wear, both circumferentially and axially, results in a variable depth of cut. The second cause for variations in the cutting force is the difference in roll surface hardness (CHAPTER III).
2. The resulting stiffness between the machine and workpiece varies with the position of the cutting tool during tool travel. Even with a constant cutting force, the deflection varies, leaving a form error on the roll body.

7.1.1 Cutting Force Variations

The consequence of the variation in the cutting force is a relative deflection between the cutting tool and the roll during the cut. Any roll surface defects prior to machining, e.g. uneven roll wear, spalls, hardness variation etc., as described in CHAPTER III, will be recopied and will remain as a form error after machining. The degree of form error reproduction depends on the ratio of cutting force stiffness R to machine tool stiffness K:

$$\mu = \frac{R_c}{K} \qquad (32)$$

Cutting force stiffness R is defined as the ratio of radial component F_r of the cutting force F_s and the depth of cut a:

$$R_c = \frac{F_r}{a}$$

The machine tool stiffness is:

$$K = \frac{F_r}{y}$$

The radial deflection between tool and workpiece is designated as y. Machine tool stiffness is often expressed in terms of the compliance

$$C = \frac{1}{K} = \frac{y}{F_r}$$

Tlusty and Koenigsberger [36] [41] show that an initial workpiece form error Δ will be re-copied due to cutting force variations as follows:

$$\delta = \frac{\mu}{1 + \mu} \Delta \qquad (33)$$

δ is the remaining form error after a cut. Tlusty and

Koenigsberger [41] determined through their research approximate values for μ, which range from 0.001 to 0.005 for engine lathes and between $\mu = 1$ to $\mu = 20$ for cylindrical grinding machines. The author was unable to obtain any values for roll turning lathes. Although specific cutting forces are higher for roll turning, the machine tool stiffness of a typical roll lathe is very much higher than that of a standard engine lathe (see following sections). The author therefore concludes that the ratio of cutting force to machine tool stiffness is smaller than or at the very worst equal to that of an engine lathe. The obtainable accuracy after turning of a roll with slight surface damage is calculated below.

Example:

Machining of a hot mill back-up roll to remove the work hardened surface. Initial form error Δ = 1.5 mm in a 3 mm diametrical roll reduction and $\mu = 0.001$. Remaining error δ after one cut:

$$\delta = \frac{\mu}{1+\mu}\,\Delta = \mu\Delta = 0.0015 \text{ mm}$$

This error is negligibly small and has no effect on the mill operation. The acceptable form error on back-up rolls is approximately 0.070 mm, based on current production standards. It is therefore possible to cut across the roll body in one single cut and achieve the desired diametrical tolerance.

The remaining form error after grinding, in contrast, is very much larger and ranges between 1.43 mm to 0.75 mm (at $\mu = 1$ to $\mu = 20$, using Equation (33)).

7.1.2 Compliance Variations

Errors caused by the stiffness between machine tool and workpiece [36] are expressed as:

$$\delta = a\ (\mu_{max} - \mu_{min}) \qquad (34)$$

This error depends only on the maximum difference in machine tool stiffness and the depth of cut. Figure 7.1 shows the changes in the resulting horizontal compliance between the workpiece and the tool, assuming a rigid workpiece and no deflection on the tool. Measurement, made by Tlusty [35] , are based on an engine lathe with 500 mm swing over the bed, for a workpiece clamped in a chuck and supported in one centre. The line "a" indicates the deformation measured parallel to the lathe centre line with the load applied on point A. The same procedure applies to the line b and c. Conclusions can be drawn for the shape of lines a, b, and c concerning the compliance of the individual machine element. It can be seen that the spindle end of the headstock, the tailstock centre and quill are mainly responsible for the deflections.

The resulting compliance consists of the compliance of the roll lathe, having an infinitely rigid workpiece, plus the compliance of the workpiece.

7.1.3 Conclusion

The remaining form error generated by variations of the cutting force was calculated and was found to be negligible, although no accurate data concerning the ratio of cutting force stiffness to machine tool stiffness was available. The author was unable to obtain any information concerning the resulting compliance of a roll turning lathe. However, the effect of relative deflections between tool and workpiece caused by a change in the cutting force and a varying compliance, on the accuracy of the turned roll, was obtained by an actual cutting test. This test was conducted on a modern heavy duty engine lathe located in a plant of Westinghouse Canada Limited, with satisfactory results. This confirmed the above calculations, and the assumption that the effect of cutting force deformations on turned roll accuracy is sufficiently small that the required accuracy can be achieved using only a single cut.

7.2 Lathe Bed

Depending on the manufacturer, the bed is either of fabricated steel box construction or of cast iron.

Most roll lathes of this size are equipped with 4 bed ways. The saddle is guided on the two front ways and is allowed to travel past the tailstock, which is guided at the two rear ways, see Figure 7.2 and Figure 7.3.

Saddle slide ways are equipped with replaceable hardened steel strips (see Figure 7.3).

Most manufacturers attempt to provide the bed with several individual box type cross sections with additional ribbing in order to maximize the stiffness of the bed.

7.3 Headstock

The problem of maximizing the spindle rigidity and minimizing the deflection of the main spindle due to loads of the workpiece and the driving torque, was emphasized by all manufacturers. The spindle is mounted in adjustable anti-friction bearings. All gears in the headstock are helical, hardened and ground.

Most machines are equipped with either two or four speed ranges, with a D.C. main drive motor.

7.4 Tailstock

The historical tendency has been to devote particular care and attention to the design of the headstock, thereby neglecting the requirements of the tailstock. The stability against chatter of the total machine tool system, however, requires that the workpiece receives maximum support at both ends. Not only the stability against chatter but also the accuracy of the finished turned roll is influenced by the tailstock. Figure 7.1 illustrates large deflections caused by an underdesigned tailstock.

Half of the roll weight and the same magnitude of the cutting force has to be absorbed by the tailstock. The tailstock should therefore be designed equivalent in capacity and rigidity to the headstock. Some drastic design differences in size and concept between various manufacturers are apparent here. Most lathe manufacturers equip the tailstock with a quill, similar to the design typical for engine lathes. The approximate maximum length of travel offered, ranges between 100 mm and 300 mm depending on manufacturer. Figure 7.4 shows a cross section of a tailstock with quill travel. Noteworthy is the built-in disc spring behind the thrust bearing which allows for the thermal expansion of the workpiece.

In contrast to this concept is the tailstock designed by Maschinenfabrik Herkules, which has no quill nor quill travel. The tailstock spindle is supported in the same manner as the headstock main spindle. Very large roller bearings are directly mounted in the body of the tailstock housing, see Figure 7.5. The tailstock spindle has a very limited axial movement (approximately 4 mm) to create the required end thrust into the roll center. This axial displacement takes place within the preloaded roller bearings. The coarse adjustment is achieved by moving the whole tailstock. These features, large bearings, the elimination of the quill and quill extension ensures maximum rigidity of the tailstock.

7.5 Saddle

The most outstanding characteristic of a modern roll lathe is the saddle design.

A typical engine lathe is equipped with an apron which projects below the saddle at the operating side. This introduces additional torsional forces on the lathe bed. Most modern roll lathes have relocated the longitudinal feed drive from the front of the machine bed to the front of the second slide way. This is a more favourable location for the drive in relation to the cutting force transmission. In addition, it allows the bed to be lowered further into the foundation, making it more accessible to the lathe operator. This can be clearly seen on Figure 7.2.

Another distinctive feature of a roll lathe suitable for the maintenance of rolls for flat rolled products is the absence of a toolpost with a traversing and swivelling topslide. This has been completely eliminated in favour of one single cross slide on which a very rigid tool carrier is mounted, see Figure 7.6, and Figure 7.2. The cutting tool is therefore always supported, e.g. when taking a heavy plunge cut. Shank tool holders as shown on Figure 7.2, are impractical due to their weight. Small tool shanks however, as shown on Figure 6.8 and Figure 6.9, are quickly changed and require little effort by the operator. The generated cutting forces, (in every position of the tool relative to the workpiece), are always directly transmitted into the box-like bed structure. This can be readily seen on Figure 7.2. The loading of the bed structure of an engine lathe in contrast, can be very different, see Figure 7.7.

Sliding surfaces of most saddles are lined with plastic wear strips.

There are several solutions for the design of the drive systems for the feed motion. All systems offered are equipped with a backlash eliminator.

Some lathes are supplied with recirculating ball nuts, preloaded against each other to eliminate backlash. Other lathe builders use a helical rack and double pinion drive system for the longitudinal traverse and a recirculating ball nut for the transverse feed motion.

CHAPTER VIII

SUMMARY

Tests at DOFASCO have proven that back-up rolls for hot strip finishing mills can be maintained by turning. The surface integrity of the turned roll suffices to maintain the required surface quality of the rolled material. Therefore, all hot mill rolls with the exception of the work rolls of the finishing mill can be maintained by turning rather than by grinding. Grinding is the commonly accepted practice in the steel industry.

Calculations showed that the accuracy of the finish turned rolls not only meet the required out-of roundness tolerance, but errors were negligibly small. This was confirmed by actual tests utilizing a modern engine lathe of Westinghouse Canada Limited. Rolls can therefore be finish turned in a single cut across the roll barrel.

Substantial cost savings result from the application of a roll turning lathe for the maintenance of DOFASCO's heavy rolls, e.g. slabbing and roughing mill rolls, hot strip mill back-up rolls and the repair of cold mill back-up rolls. The economic evaluation was based on conservative machining time estimates and the author believes that further improvements can be achieved.

Extensive cutting tests need to be conducted once the proposed new lathe is installed to determine the most suitable tool materials and optimum cutting conditions for the various rolls. Costs can be reduced by selecting cutting inserts permitting eight cutting edges rather than four. For the calculation of optimum tool life, Feldmühle [26] limited the permissable tool wear to 0.2 mm flank wear. Binns [34] in contrast allowed up to 0.8 mm flank wear. Further tests are required to determine the maximum allowable tool wear.

In order to assure the acquisition of a reliable and accurate roll turning lathe, it is necessary to write stringent machine tool specifications and acceptance tests. Based on the author's experience, it is not standard practice in the steel industry to utilize this type of testing and specifications when purchasing these very expensive roll maintenance machine tools. The author knows of several instances where the installation of roll grinders and roll lathes resulted in performances extremely below the expected.

BIBLIOGRAPHY

CHAPTER I

1. G. W. Rowe, "An Introduction to the Principles of Metalworking", London, Edward Arnold Ltd., 1965, Reprinted in 1968.

2. Z. Wusatowski, "Fundamentals of Rolling", Pergamon Press, Oxford, 1969.

3. "SKF Bearings in Rolling Mills", published by SKF, Sweden, 1971.

4. J. M. Alexander, R. C. Brewer, "Manufacturing Properties of Materials", D. Van Nostrand Company Ltd., London, 1963. Reprinted 1968.

5. H. E. McZannon, Editor, "The Making, Shaping and Treating of Steels", 9th Edition, Copyright by United States Steel. Printed by Harbich & Held, Pittsburgh, 1970.

6. "FAG Rolling Bearings for Rolling Mills", FAG Publication No. 17200EA, Schweinfurt, 1976.

CHAPTERS II to V

7. F. H. Allison, C. E. Peterson, "Modern Manufacture and Use of Cast Rolling Mill Rolls", Iron and Steel Engineers, Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1954.

8. J. W. Linhart, "Differential Heat Treatment of Rolls to Improve Life and Performance", Iron and Steel Engineer, Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1972.

9. F. W. Jones, "Hardened Steel Rolls", Steel and Coal. Published by Association of Steel and Coal Engineers, London, 1962.

10. Williams and Boxall, "Roll Surface Deterioration in Hot Strip Mills", Journal of the Iron and Steel Institute. Published by the Iron and Steel Institute, London, 1965.

11. D. Yorke, "The Research Program", from Benefits, Improvements and Ideas from Roll Research Program, Iron and Steel Engineers Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1966.

12. M. D. Stone, "A Mathematical Approach", from Benefits, Improvements and Ideas from Roll Research Program, Iron and Steel Engineers Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1966.

13. L. J. Spivak, "Practical Aspects" from Benefits and Ideas from Roll Research Program, Iron and Steel Engineers Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1966.

14. S. Stasko, "Evaluation of Mill Factors", Iron and Steel Engineers Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1966.

15. F. H. Allison, "Introduction to the Spalling Project", from "Benefits, Improvements and Ideas from Roll Research Program", Iron and Steel Engineers Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1966.

16. J. M. Dugan, "A Study of the Microstructure of Rolls for Blooming and Slabbing Mill Applications", Iron and Steel Engineer, Year Book. Published by Association of Iron and Steel Engineers, Pittsburgh, 1966.

17. "Industry Practice Guide for SI METRIC UNITS in the CANADIAN STEEL INDUSTRY". Published by The Task Force for Metric Conversion in the Canadian Steel Industry, Burlington, 1975.

CHAPTER VI to VII

18. Bruins, Dräger, "Werkzeuge u. Werkzeug-Maschinen", Carl Hanser Verlag, München, 1975.

19. "Machining Data Handbook", compiled by Technical Staff of the Machinability Data Centres, Metcut Research Association Inc., 2nd Edition, Cincinnati, 1973.

20. Private Communications from Dr. J. Tlusty.

21. H. S. Kalish, "Some Plain Talk about Carbides", The Society of Carbide Engineers, 7th Carbide Cutting and Forming Seminar, Hamilton, Canada, 1975.

22. J. Tlusty, "Breakage of Cutting Tools". The Society of Carbide Engineers, 7th Carbide Cutting and Forming Seminar, Hamilton, Canada, 1975.

23. I. Yellowley, "The Wear of Cutting Tools", The Society of Carbide Engineers, 7th Carbide Cutting and Forming Seminar, Hamilton, Canada, 1975.

24. H. L. Patts, "Understanding Micrograin Cemented Carbides", The Society of Carbide Engineers, 7th Carbide Cutting and Forming Seminar, Hamilton, Canada, 1975.

25. Kazuki Ogawa, et al, "Cutting Performances and Practical Merits of Carbide Ceramics", Nippon Tungsten Review, September 1973, Volume 6, Nippon Tungsten Co. Ltd., Shiobaru, Japan, 1973.

26. "Feldmühle SPK-Werkzeuge fur Hartguss und Hartlegierungen", published by Feldmühle A. G., Plochingen, Germany, 1977.

27. "Degusit - Schneidplatten aus Oxidkeramik", publication No. S840, Degussa, Frankfurt/M. Germany.

28. J. Binns, "Ceramic Cutter Performance on Rough Turning and Hogging Cuts", American Society of Tool and Manufacturing Engineers, Paper No. 633, Detroit, 1965.

29. K. Gettelman, "Hogging With Ceramic is a Rigid Proposition", Modern Machine Shop, Gordon Publications, Cincinnati, 1977.

30. "Taking Interrupted Cuts With Ceramics", Manufacturing Engineering, Published by Society of Manufacturing Engineers, Dearborn, Michigan, 1976.

31. H. S. Kalish, "Titanium Carbides - How and Where Cemented Titanium Carbide Should be Used", The Society of Carbide Engineers, 7th Carbide Cutting and Forming Seminar, Hamilton, Canada, 1975.

32. I. D. Murray, "The Titanium Carbide Coating Concept", The Society of Carbide Engineers, 7th Carbide Cutting and Forming Seminar, Hamilton, Canada, 1975.

33. D. E. Herzog, "Now: Turn Hardened Steels and Tough Superalloys with new Cutting Tool Materials", Manufacturing Engineering. Published by Society of Manufacturing Engineers, Dearborn, Michigan, October 1975.

34. J. Binns, "Rough Turning and Hogging with Ceramic Cutters", American Society of Tool and Manufacturing Engineers, Publication No. SP 64 - 40, Detroit, 1964.

35. F. Koenigsberger, J. Tlusty, "Machine Tool Structures", Volume 1, Pegamon Press, 1970.

36. J. Tlusty, F. Koenigsberger, "Specifications and Tests of Metal Cutting Machine Tools", University of Manchester, C.I.R.P. Conference, 1969.

37. K. F. Althoff, "Specifische Schnittwerte für die Zerspanung mettallischer Werkstoffe beim Drehen und Fräsen", Stahl u. Eisen, No. 6, March 1975. Published by Verein Deutscher Eisenhüttenleute, Düsseldorf, 1975.

38. F. Schwerd, "Spanende Werkzeugmaschinen", Springer Verlag, Berlin, 1956.

39. F. Koenigsberger, "Design Principles of Metal Cutting Machine Tools", McMillan Comp., New York, 1964.

40. F. Sass, Ch. Bouche, A. Leitner, "Dubbel's Taschen-Buch für den Maschinenbau", Volume II, 12th Edition, Springer-Verlag, Berlin, 1961.

41. J. Tlusty, F. Koenigsberger, "New Concept of Machine Tool Accuracy", Annals of the C.I.R.P., Vol. XVIV, pp. 261-273, printed in Great Britain, 1971.

PAMPHLETS PUBLISHED BY MACHINE TOOL BUILDERS:

42. "Heavy Duty Lathes", Maschinen-fabrik Herkules, Siegen, W. Germany.

43. "Large Capacity Turning Machines", Publication No. 211, Hoesch Maschinen-fabrik Deutschland, Dortmund, W. Germany.

44. "Engine Lathes", Innocenti Santeustacchio, Brescia, Italy, 1973.

45. "Walzenschrupp-Drehmaschine", VEB Werkzeugmaschinenkombinat, Betrieb, John Schehr, Meuselwitz, E. Germany.

46. "Heyligenstaedt Heavy-Duty Lathes", Heyligenstaedt & Co., Werkzeugmaschinenfabrik, Giessen, W. Germany.

TABLE 1

COMPARISON OF ROLL SEPARATING FORCES
88" SLABBING MILL
MATERIAL: SAE 1010

PASS NO.	SLAB THICK-NESS mm	SLAB WIDTH mm	SPEED m/min	APPROX. TEMP. °C	ACTUAL ROLL FORCE MN	(1) ROLL FORCE ELEMENTARY ASSM'T MN	(2) ROLL SEPAR. FORCE MN	(3) FORCE FROM PRESSURE DIST. MN	ACTUAL ROLL FORCE PER WIDTH N/mm
0	679	1,470							
1	628	1,440	152	1,250					
2	573	1,440	158	1,250	10.676	5.556	9.746	5.703	7,259
3	520	1,420	174	1,240	11.120	5.889	9.456	5.982	7,803
4	468	1,420	175	1,240	10.498	5.823	8.487	5.961	7,367
↓									
8	267	1,370							

(1) Elementary assessment of roll load calculation as per Section 1.3.1.1.

(2) Calculation of roll separating force as per Section 1.3.1.2.

(3) Calculation of roll separating force based on roll pressure distribution as per Section 1.3.1.4.

Work Roll Diameter D = 1,120 mm.

Approximate spread per pass 50 mm.

TABLE 2

COMPARISON OF GENERATED ROLL PRESSURES
88" SLABBING MILL
MATERIAL: SAE 1010

PASS NO.	SLAB THICK-NESS mm	SLAB WIDTH mm	SPEED m/min	APPROX. TEMP. °C	ACTUAL ROLL PRESSURE MPa*	(1) ROLL PRES. ELEMENTARY ASSM'T MPa	(2) MEAN ROLL PRESSURE MPa
0	679	1,470					
1	628	1,440	152	1,250			
2	573	1,440	158	1,250	41.64	22.06	39.23
3	520	1,420	174	1,240	43.78	22.06	37.23
4	468	1,420	175	1,240	42.40	23.44	34.34
↓							
8	267	1,370					

$$\text{* Actual Roll Pressure} = \frac{\text{Actual Roll Separating Force}}{\text{Projected Area of Roll Contact}}$$

(as per Section 1.3.1.1)

(1) Elementary Assessment of roll pressure as per Section 1.3.1.1.

(2) Mean Roll Pressure from Figure 1.2.4 of Reference 4.
Work Roll Diameter D = 1,120 mm
Approximate Spread per pass = 50 mm

TABLE 3

COMPARISON OF ROLL SEPARATING FORCES
7 STAND HOT STRIP FINISHING MILL
MATERIAL: SAE 1010

PASS NO.	STRIP THICK-NESS mm	SPEED m/min	APPROX. TEMP. °C	ACTUAL ROLL SEP. FORCE MN	(1) ELEMENTARY ASSESS. OF ROLL FORCE MN	(2) ROLL SEPAR. FORCE MN	(3) FORCE FROM PRESSURE DIST. MN	ACTUAL ROLL FORCE PER WIDTH N/mm
0	30.58							
1	18.34	86	1,100	12.01	5.25	11.56	6.85	10,035
2	11.15	125	1,000	11.12	5.38	10.76	7.96	9,282
3	7.85	186	900	11.12	4.58	11.39	6.63	9,283
4	5.76	247	850	11.12	4.00	11.21	6.18	9,283
5	4.27	311	820	8.89	3.56	11.96	5.96	7,425
6	3.34	375	800	6.67	2.85	11.52	4.67	5,569
7	2.77	430	780	5.56	2.45	8.89	3.96	4,641

(1) Elementary Assessment of roll load as per Section 1.3.3.1.

(2) Calculation of roll separating force as per Section 1.3.3.2.

(3) Calculation of roll separating force as based on roll pressure distribution as per Section 1.3.3.3.

Approximate Work Roll Diameters: D = 724 mm.

Strip Width: w = 1,197 mm.

TABLE 4

COMPARISON OF ROLL PRESSURES
7 STAND HOT STRIP FINISHING MILL
MATERIAL: SAE 1010

PASS NO.	STRIP THICK-NESS mm	SPEED m/min	APPROX. TEMP. °C	ACTUAL ROLL PRESSURE MPa	(1) ROLL PRES. ELEMENTARY ASSM'T MPa	(2) MEAN ROLL PRESSURE MPa
0	30.50					
1	18.34	86	1,100	151.34	50.74	183.47
2	11.15	125	1,000	182.09	67.70	176.50
3	7.85	186	900	268.69	84.68	264.75
4	5.76	247	850	338.32	93.08	313.71
5	4.27	311	820	319.09	98.11	392.17
6	3.34	375	800	310.74	101.49	490.21
7	2.77	430	780	312.68	104.87	470.56

(1) Elementary assessment of roll pressure as per Section 1.3.1.1.

(2) Mean roll pressure from Figure 1.2.1 to 1.2.3 of Reference [4].

Work roll diameter D = 724 mm.

Strip width w = 1,197 mm.

TABLE 5

COMPARISON OF ROLL SEPARATING FORCES AND ROLL PRESSURES
5 STAND 72" CONTINUOUS COLD REDUCTION MILL
MATERIAL: SAE 1010

PASS NO.	THICK-NESS mm	SPEED m/min	STRIP TENSION MPa	ACTUAL ROLL FORCE MN	ACTUAL ROLL PRESSURE MPa	ACTUAL ROLL FORCE PER WIDTH N/mm	(1) ELEM. ASSM'T OF ROLL LOAD MN	(1) ELEM. ASSM'T OF ROLL PRESSURE MPa	(2) ROLL FORCE MN	(2) ROLL PRESSURE MPa
0	3.05	596								
1	2.49	643	173	8.05	662	7,548	5.60	462	9.29	758
2	1.93	927	155	8.89	731	8,336	7.38	607	10.99	1,000
3	1.52	1,179	151	7.96	765	7,460	7.02	675	12.45	1,200
4	1.17	1,500	148	9.56	1,000	8,966	7.02	738	14.10	1,448
5	1.14	1,584	5 8	6.63	2,151	6,217	2.31	758	5.87	1,917

* Actual Pressure $= \dfrac{\text{ACTUAL FORCE}}{w\sqrt{R\Delta h}}$

(1) Elementary assessment of roll loads as per Section 1.4.1.1, neglecting interstand strip tension.

(2) Calculation of roll separating force and pressures as per Section 1.4.1.2, neglecting interstand strip tension.

Approximate work load diameter D = 467 mm.

Width of Strip w = 1,067 mm.

TABLE 6

ROLL MATERIALS USED AT DOFASCO

ITEM NO.	MILL	WORK ROLLS		BACK-UP ROLLS	
		MATERIAL	HARDNESS SCLERO-SCOPE "C"	MATERIAL	HARDNESS SCLERO-SCOPE "C"
1	HOT MILL Slabbing and roughing mills.	Cast alloyed steel. 830 MPa tensile strength.	38 - 40	NOT APPLICABLE	NOT APPLICABLE
2 3	HOT STRIP Finishing mills.	Chilled cast iron and Cast Steel (410 MPa tensile strength)	78 48 - 50	Cast steel (620 MPa tensile) and differentially hardened steel (1130 MPa tensile strength)	40 - 50 60 - 65
3 4	COLD MILLS	Forged steel.	93 - 98	Forged steel (solid) (1100 MPa tensile strength) and Forged steel (sleeved) (up to 1580 MPa tensile)	58 - 63 58 - 63

TABLE 7

DOFASCO ROLL DIMENSIONS
(in mm)

MILL	ITEM NO.	WORK ROLL MAXIMUM DIA.	WORK ROLL BARREL LENGTH	WORK ROLL TOTAL LENGTH	BACK-UP ROLL MAXIMUM DIA.	BACK-UP ROLL BARREL LENGTH	BACK-UP ROLL TOTAL LENGTH
HOT MILLS							
88" - 2 Hi Slabbing Mill	1	1143	2235	5750	---	---	---
66" - 2 Hi Roughing Mill	1	984	1676	4650	---	---	---
7 Stand 66" Finishing Mill	2 & 3	730	1676	4060	1422	1676	3880
COLD MILLS	3 & 4						
72" Cold Mill - 5 Stands		616	1828	4010	1537	1845	4845
66" Cold Mill		480	1676	3470	1378	1676	4445
56" Cold Mill - 5 Stands		546	1422	3640	1420	1422	4190
#5 - 56" Cold Mill		427	1422	3210	1486	1422	4120
#4 - 56" Cold Mill		362	1422	2970	1435	1422	4190
42" Cold Mill		473	1066	2740	1105	1067	3536

TABLE 8

MECHANICAL AND PHYSICAL PROPERTIES OF TUNGSTEN CARBIDES

TOOL MATERIAL	TUNGSTEN CARBIDE CONTENT % - WEIGHT	TITANIUM CARBIDE CONTENT % - WEIGHT	COBALT CONTENT % - WEIGHT	HARDNESS ROCKWELL "A" SCALE	TRANSVERSE RUPTURE STRENGTH N/mm^2
Straight Carbides:					
Grade C-1	94	--	6	91.2	2,180
Grade C-2	91	--	9	90.3	1,890
Grade C-3	95.5	--	4.5	92.2	1,380
Grade C-4	97	--	3	92.8	1,200
Steel Cutting Carbides:					
Grade C-5	80	6	14	90	1,720
Grade C-6	82	8	10	90.5	1,480
Grade C-7	80	12	8	91.5	1,200
Grade C-8	84	10	6	92	1,380

NOTE: Compression strength of above grades vary from 3800 N/mm^2 to 4800 N/mm^2. Elastic Modulus varies from 0.52 MN/mm^2 to 0.69 MN/mm^2. (from references [20] , [19] , [21])

TABLE 9

MECHANICAL AND PHYSICAL PROPERTIES AT ROOM TEMPERATURE OF SOME TOOL MATERIALS

TOOL MATERIAL	HARDNESS ROCKWELL "A"	DENSITY $\times 10^3$ kg/m^3	TRANSVERSE RUPTURE STRENGTH N/mm^2	ELASTIC MODULUS $\times 10^3$ N/mm^2
WC - Co (C_1 to C_4)	90.0 - 93.0	14.6 - 15.2	1200 - 2070	550
WC - TiC - Co (C_5 to C_8)	90.5 - 92.0	9.9 - 14.0	1200 - 1480	550
Micrograin C.C. (Carmet)	90.0 - 93.0	14.0 - 14.9	2400 - 3450	550
TiC (C_5 to C_8)	91.5 - 93.5	3.6 - 5.8	1380 - 1900	410 - 440.
Ti Coated Carbide (Carboloy 500)	90 Substrate 93 Coat		1270	550
Ceramics sintered AL_2O_3	93.0 - 94.0	3.9	345	
Hot Pressed AL_2O_3	93.0 - 94.0	4.0	482	
Hot Pressed AL_2O_3 - 30 TiC	93.0 - 94.0	4.25	517	
Cubic Boron Nitride (Borazon)	(220) 4500 HV	3.48	193 - 290	

Values of different sources vary significantly. (from references 19 to 32).

TABLE 10

PRACTICALLY ACHIEVED ROLL TURNING DATA

CUTTER MATERIAL AND WORKPIECE MATERIAL	ROUGHING CUTS Deep Cuts in Skin 13mm to 50 mm deep, 16 mm sq. ganged cutters.		SEMI-FINISH CUTS Deep Cuts, No Skin, Clean Surf. 13mm deep, 16mm sq. ganged cutters		FINISH CUTS Light Cuts only, No Skin 13mm deep or less, ½" to 1¼" dia. button.	
	SPEED m/min	FEED mm/r	SPEED m/min	FEED mm/r	SPEED m/min	FEED mm/r
CUTTER: Tungsten Carbide WORKPIECE: Iron & Steel 30 to 80 Shore	15 - 75	.254 - 2.54	27 - 120	.305 - 1.905	27 - 120	.508 - 2.28
CUTTER: Titanium Carbide WORKPIECE: Steel only 40 to 60 Shore	---	---	35 - 150	.254 - 1.27	35 - 150	.508 - 2.28
CUTTER: Ceramic WORKPIECE: Steel Only 45 to 60 Shore	---	---	60 - 180	.381 - 1.27	60 - 180	.254 - 2.28
WORKPIECE: Iron Only 50 to 75 Shore	45 - 120	.635 - 1.27	60 - 180	.635 - 1.27	60 - 180	.635 - 2.28
CUTTER: Cubic Boron Nitride WORKPIECE: Iron & Steel 70 to 100 Shore	---	---	(20mm max. depth of cut.) 75 - 120	.254 - .635	(3mm max. depth of cut.) 60 - 180	.381 - .889

Reproduced from Gettelman [29].

TABLE 11

CALCULATION FOR MAXIMUM POWER

ROLL MATERIAL	ITEM NO.	DEPTH OF CUT a mm	FEED RATE s_{MAX} mm/r	CHIP THICKNESS $h_{AVG.}$ mm	SPECIFIC FORCE F_s N/mm^2	SPEED v m/min	TOOL MATERIAL	REQUIRED POWER P_c kW
Forged Steel 830MPa Tensile Strength 38 - 40 Shore	1	3.05	2.28	0.79	2,000	120 106	WC WC	28.3 23.8
Cast Alloy Steel 620MPa Tensile Strength 40 - 50 Shore	2	3.05	2.28	0.79	1,586	120 91	WC WC	22.4 14.9
Forged Alloy Steel 1100MPa Tensile Strength 60 - 65 Shore	3	3.05	1.27	0.43	2,826	152 106 182 120	TiC TiC Ceramic Ceramic	27.6 16.4 33.6 22.4
Forged Alloy Steel 1580 MPa Tensile Strength 58 - 63 Shore	4	3.05	1.27	0.43	4,688	152 120	Ceramic Ceramic	46.2 37.3

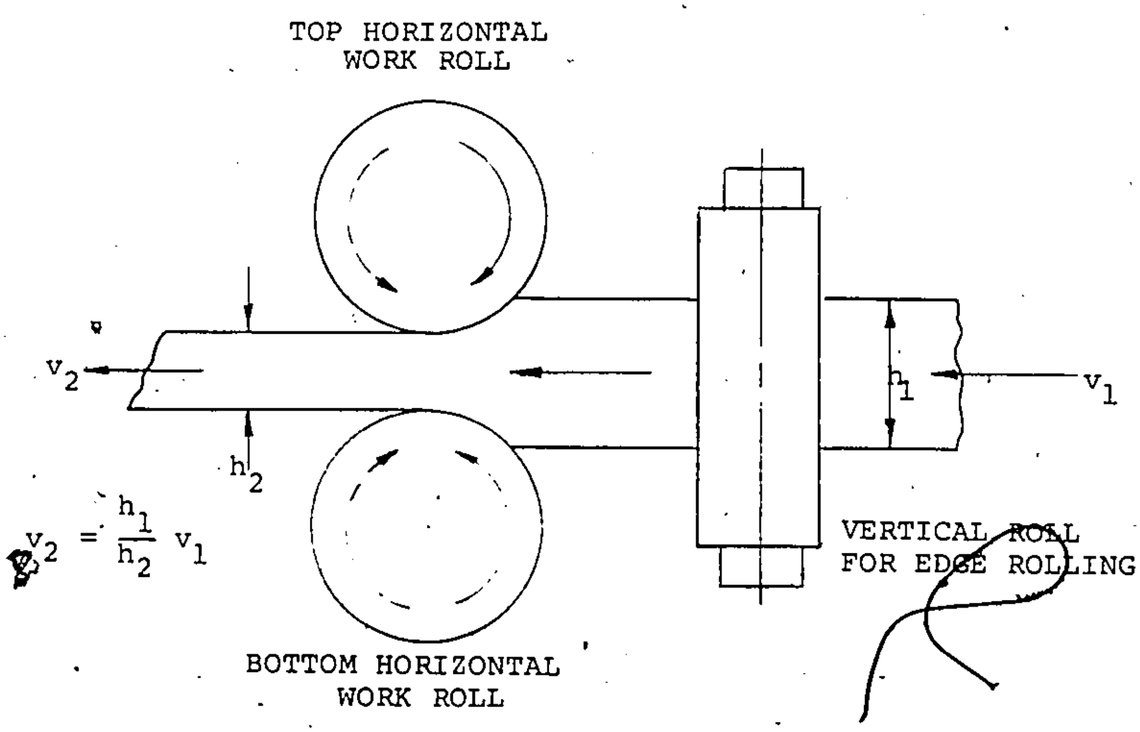


FIG. 1.0

HOT MILL - 2 HI UNIVERSAL MILL

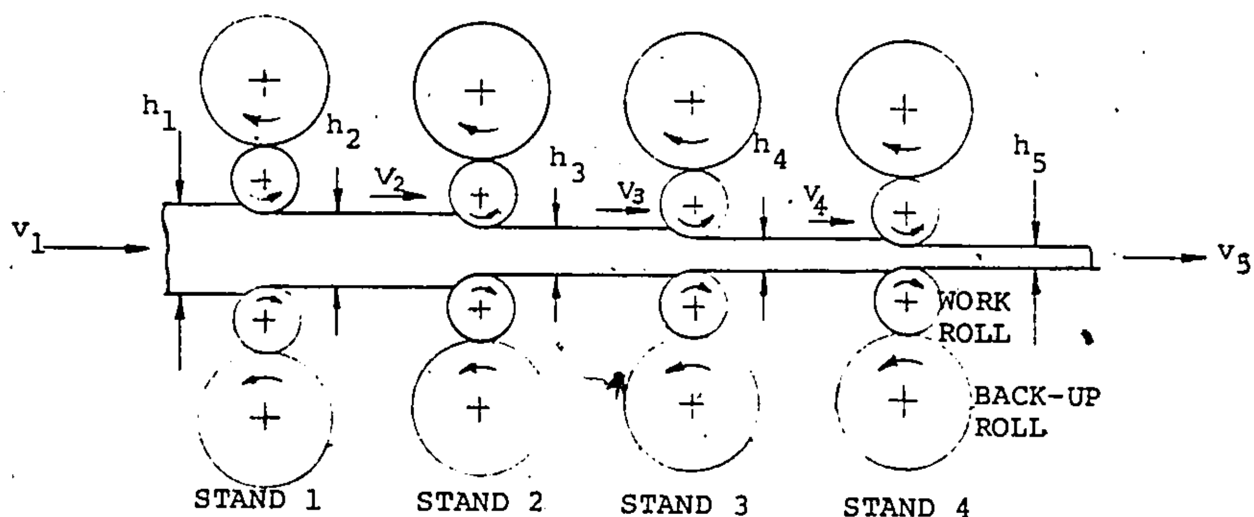


FIG. 1.1

4 HI CONTINUOUS MILL

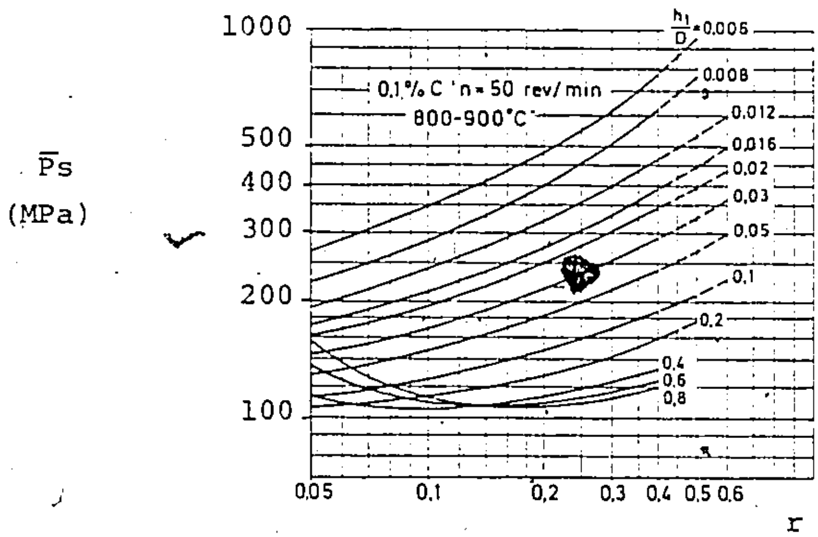


FIG. 1.2.1

ROLL PRESSURE FOR 0.1% C

STEEL AT 800 TO 900°C

FROM REFERENCE [3]

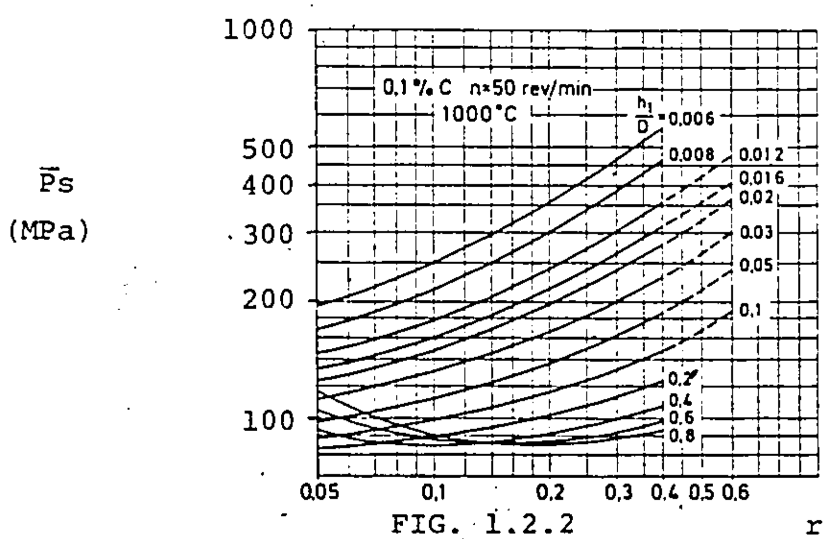


FIG. 1.2.2

ROLL PRESSURE FOR 0.1% C

STEEL AT 1,000°C

FROM REFERENCE [3]

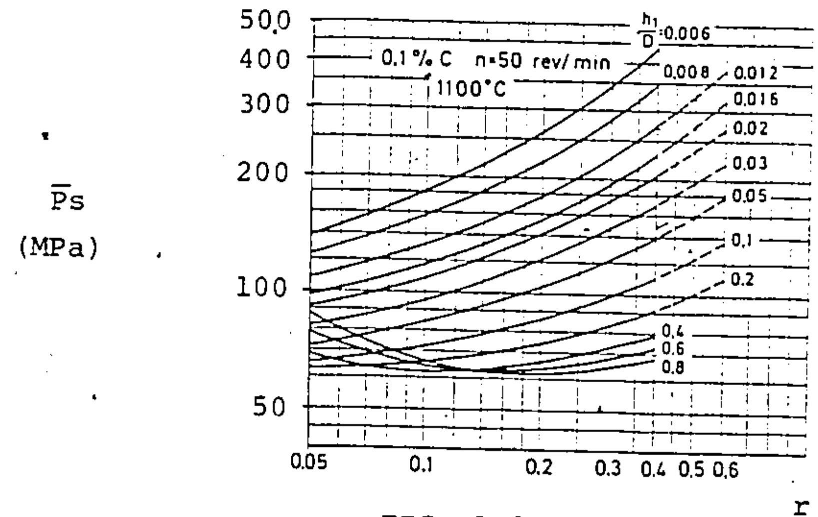


FIG. 1.2.3

SPECIFIC ROLL PRESSURE $\overline{P}_s$

STEEL AT 1,100°C

FROM REFERENCE [3]

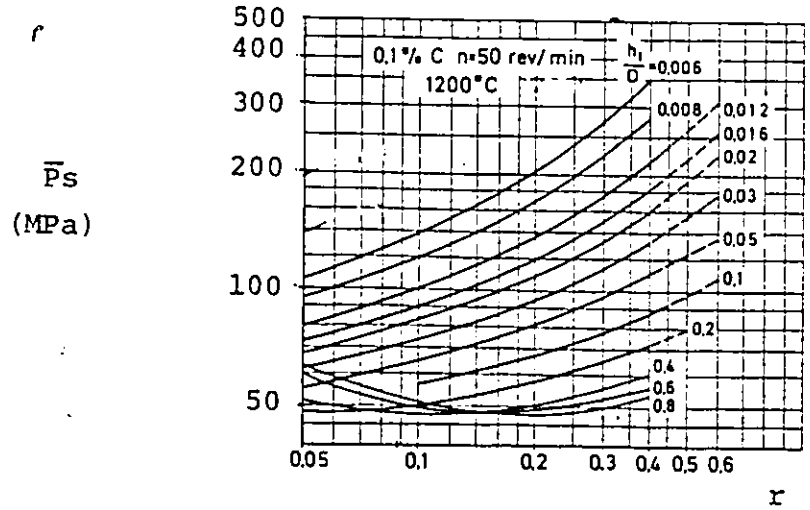


FIG. 1.2.4

SPECIFIC ROLL PRESSURE $\overline{P}_s$

STEEL AT 1,200°C

FROM REFERENCE [3]

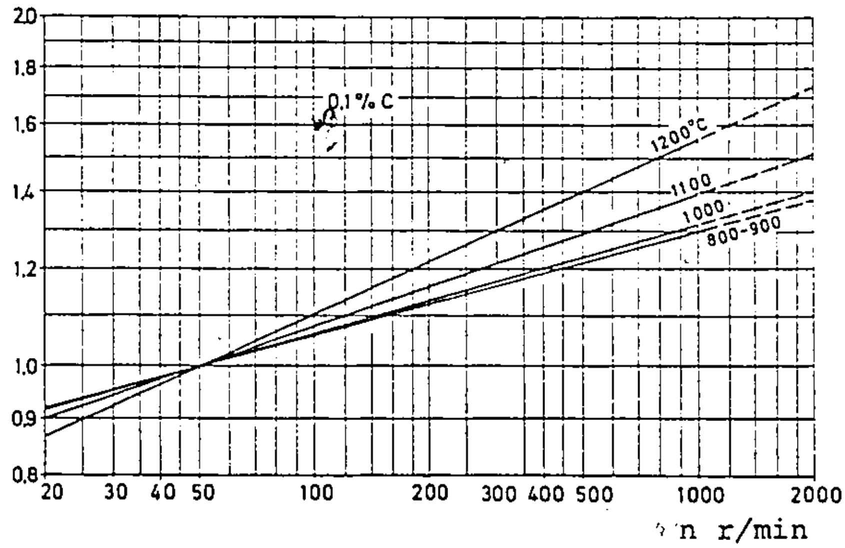


FIG. 1.3

SPEED FACTOR f_n

FOR 0.1% C STEEL

FROM REFERENCE [3]

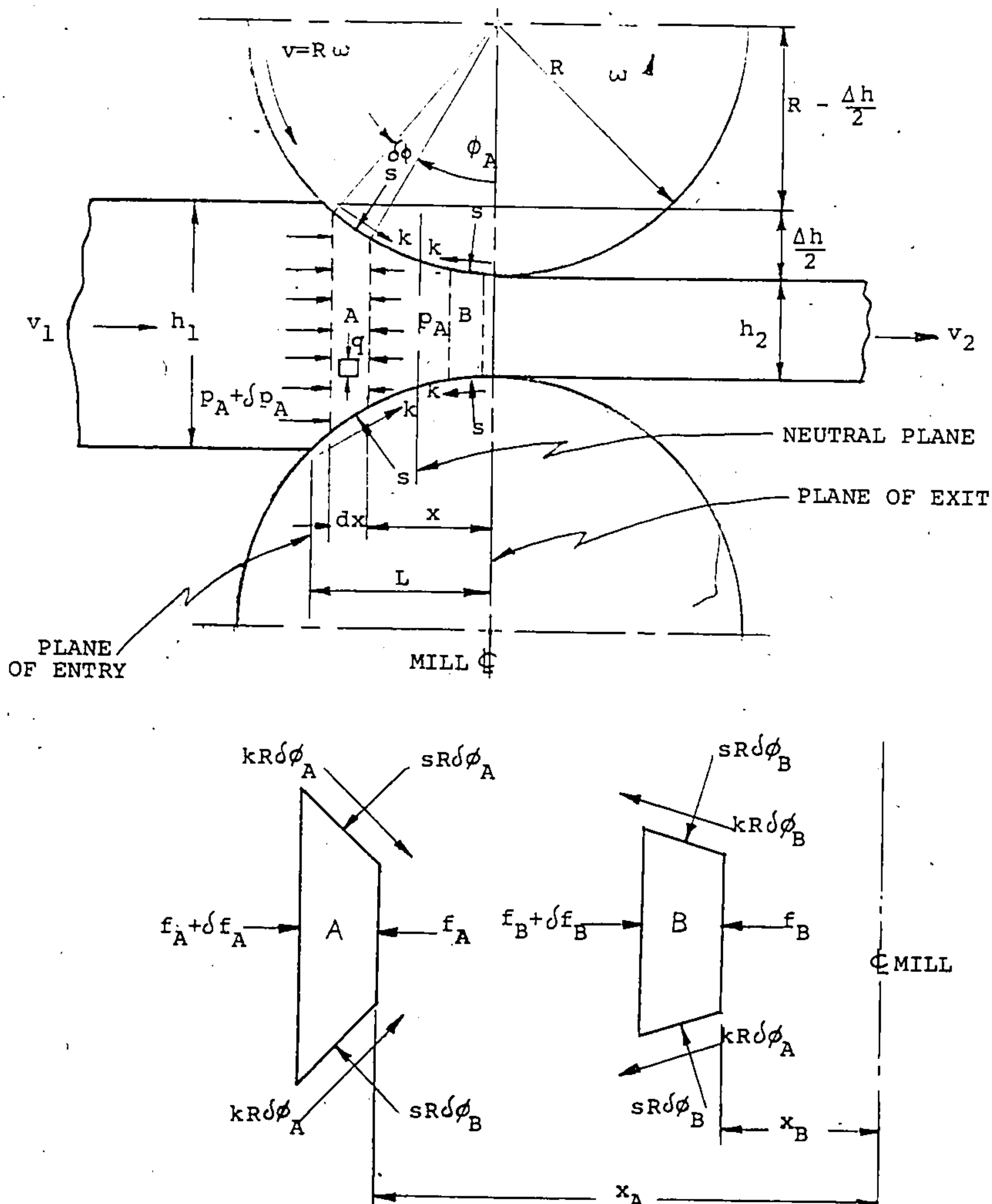


FIG. 1.4

SECTION OF DEFORMATION ZONE SHOWING STRESSES AND FORCES ACTING ON TWO ELEMENTS ON EACH SIDE OF NEUTRAL PLANE.
(from reference [1] and [4])

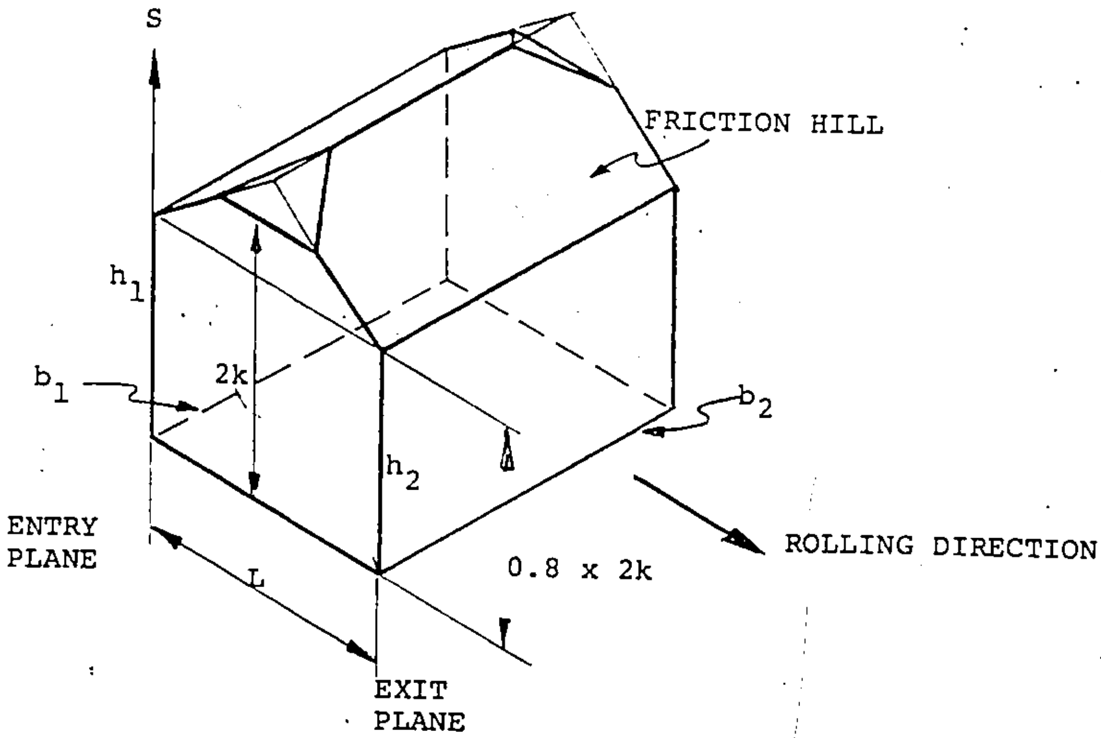


FIG. 1.5

FRICTION HILL IN HOT ROLLING OF INGOT
(from reference [4])

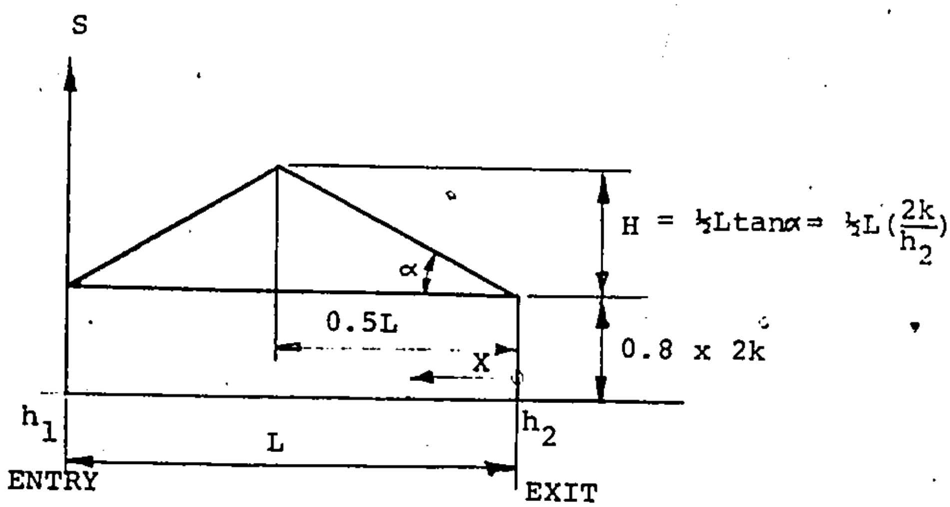


FIG. 1.6

FRICTION HILL IN HOT ROLLING OF STRIPS
(from reference [4])

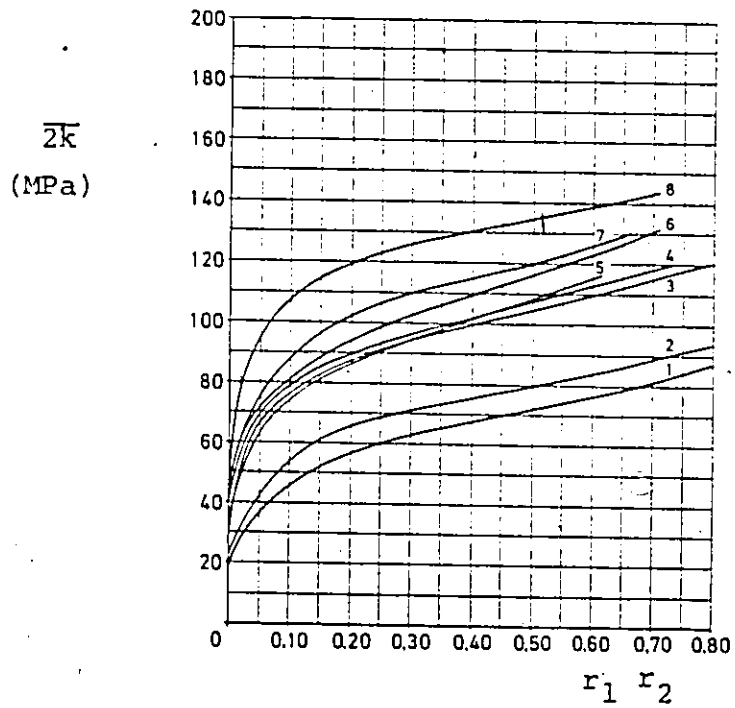


FIG. 1.7

YIELD STRESS CURVES FOR PLANE STRAIN

0 08 % C STEEL -1
0.17 % C STEEL -2
0.36 % C STEEL -3
0.51 % C STEEL -4
0.66 % C STEEL -5
0.81 % C STEEL -6
1.03 % C STEEL -7
1.29 % C STEEL -8

FROM REFERENCE [3]

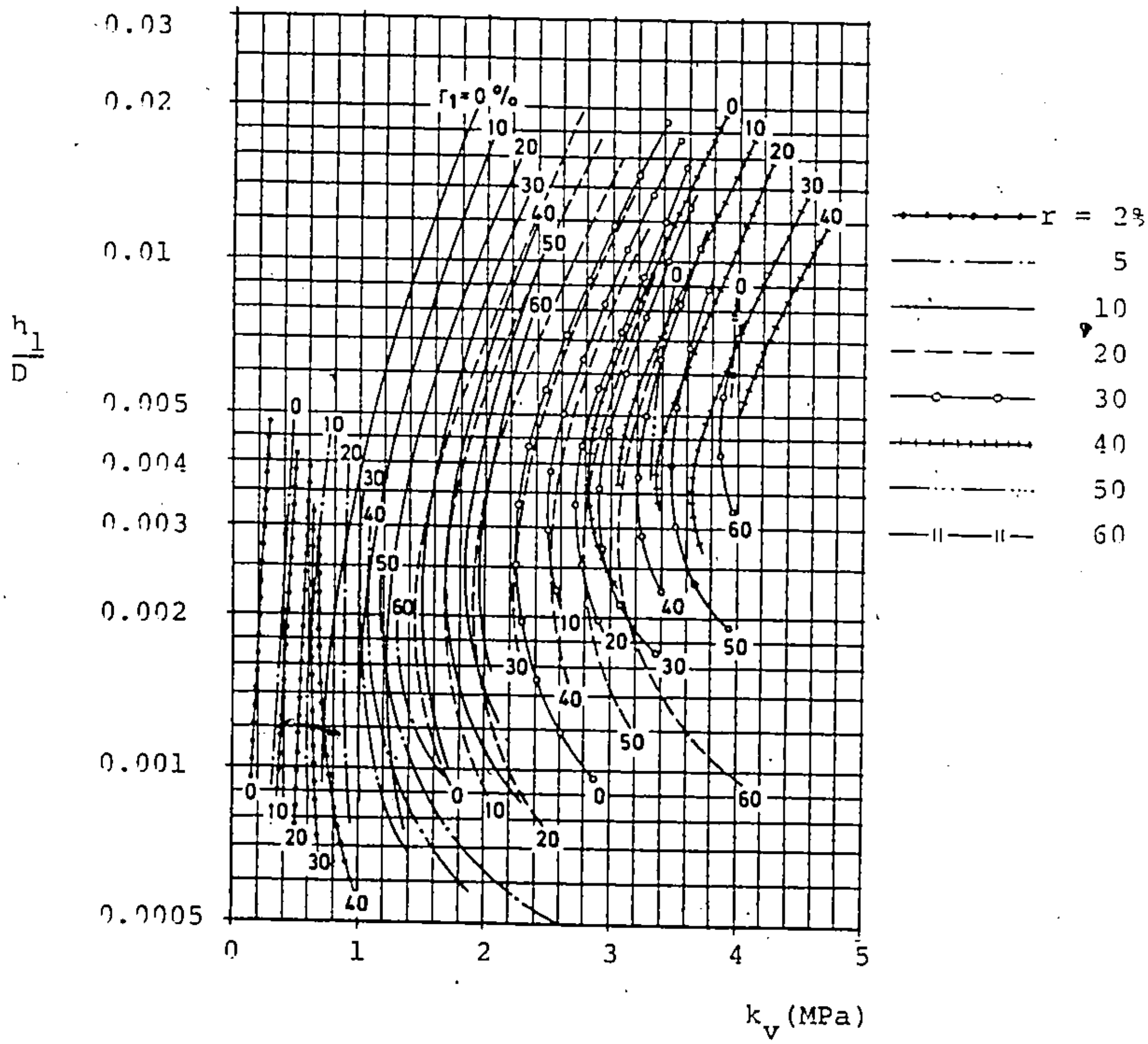


FIG. 1.8

ROLL FORCE COEFFICIENT k_v

for 0.08 to 0.15% C steel, v = 25m/min

r_1 = PRE-REDUCTION, e.g. TOTAL REDUCTION BEFORE PASS OF ANNEALED STRIP.

r = LINEAR REDUCTION IN PASS.

(from reference [3])

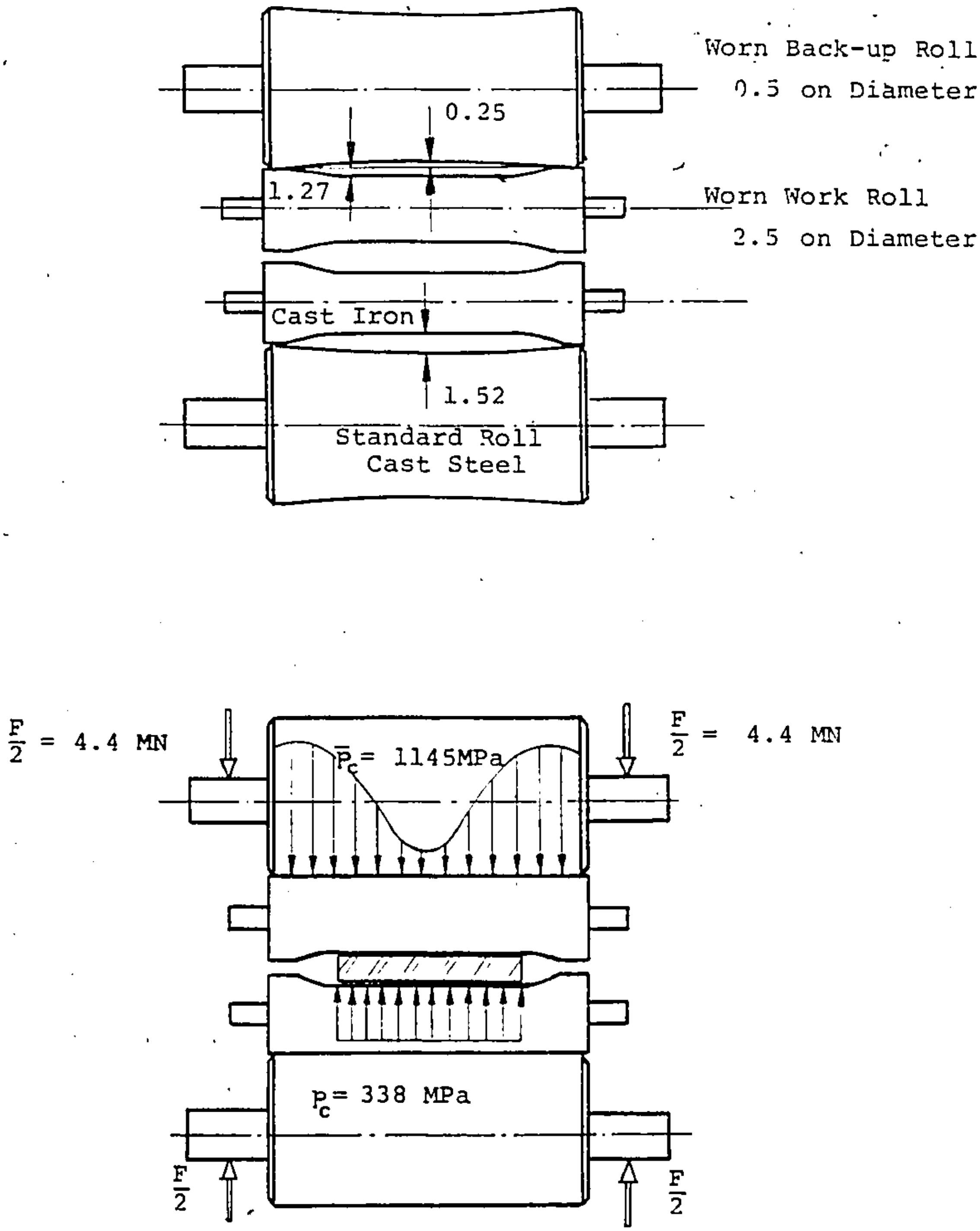
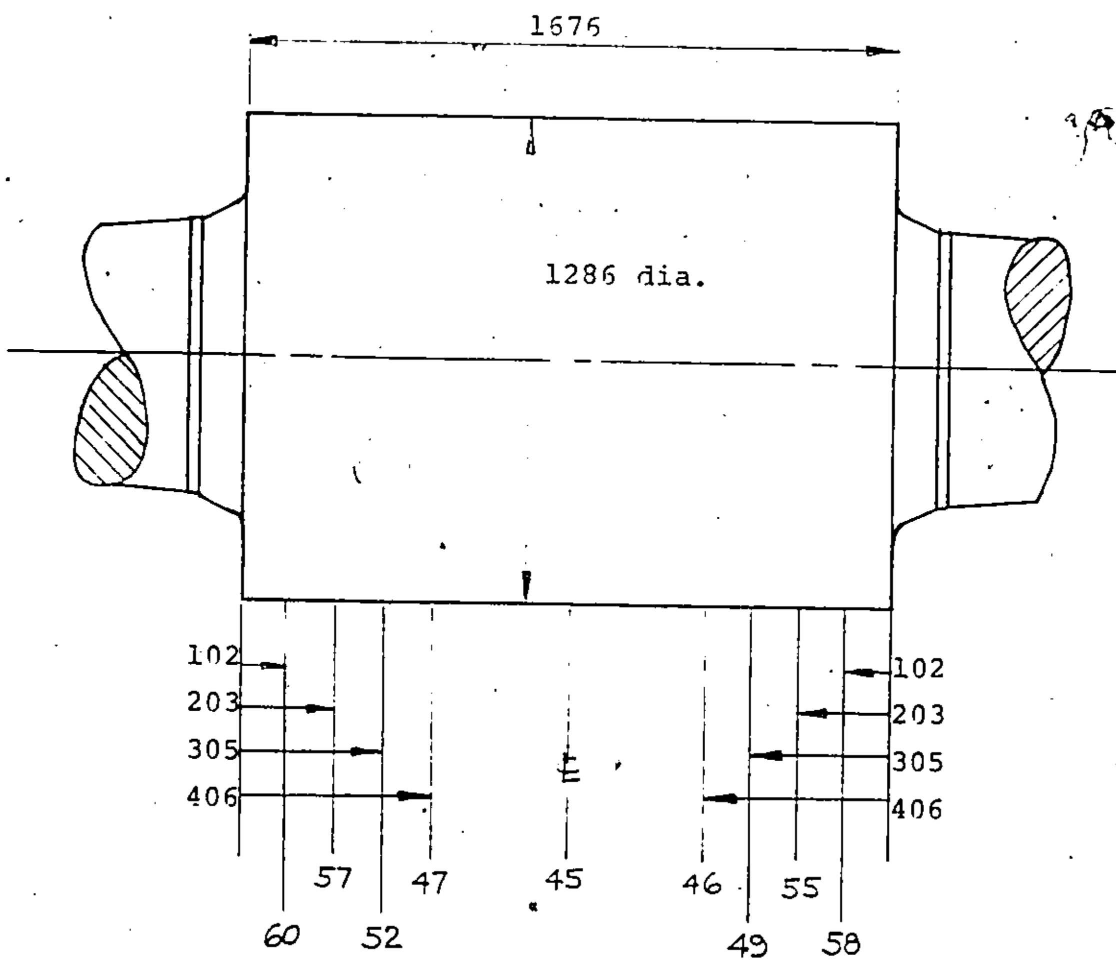


FIG. 3.0

7 STAND HOT STRIP MILL, #5 STAND

Contact pressure distribution with worn work rolls and worn back-up rolls



SHORE HARDNESS (SCLEROSCOPE "C")

FIG. 3.1

HARDNESS DISTRIBUTION ACROSS ROLL FACE

1676 × 1286 DIA. HOT STRIP MILL BACK-UP ROLL

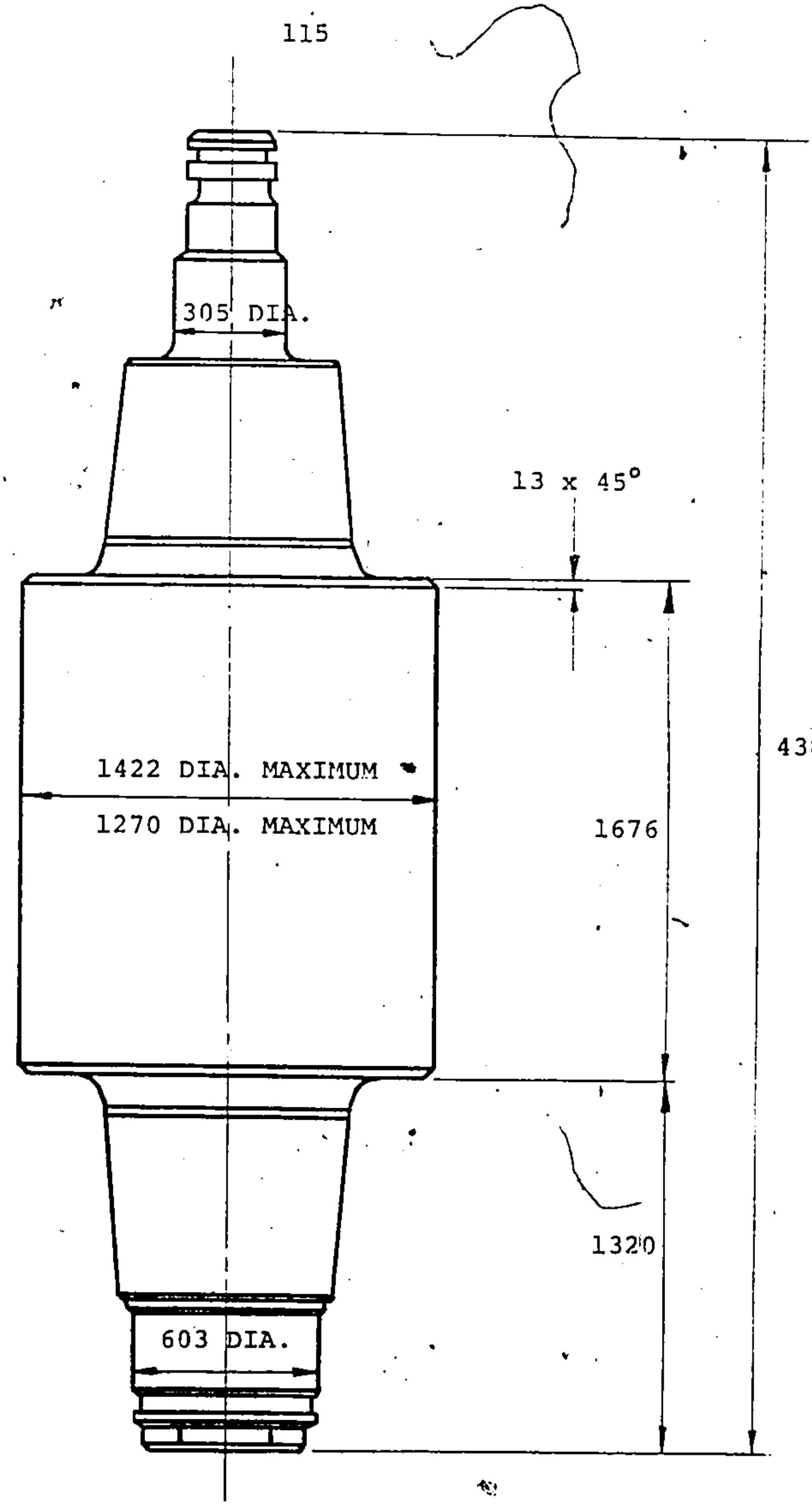


FIG. 6.0

BACK-UP ROLL

HOT STRIP FINISHING MILL

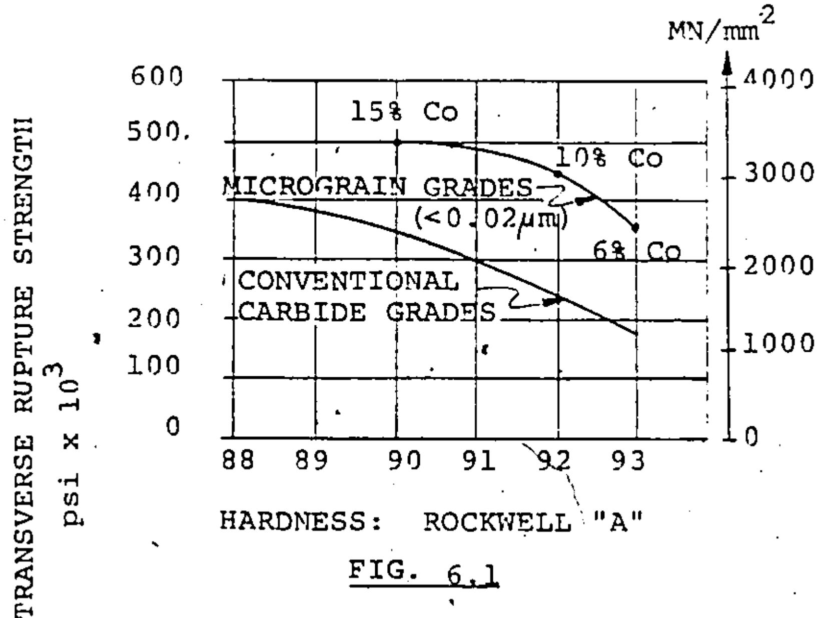


FIG. 6.1

Relationship between Rockwell "A" Hardness and Transverse Rupture Strength of Tungsten Carbides.

(reference [24])

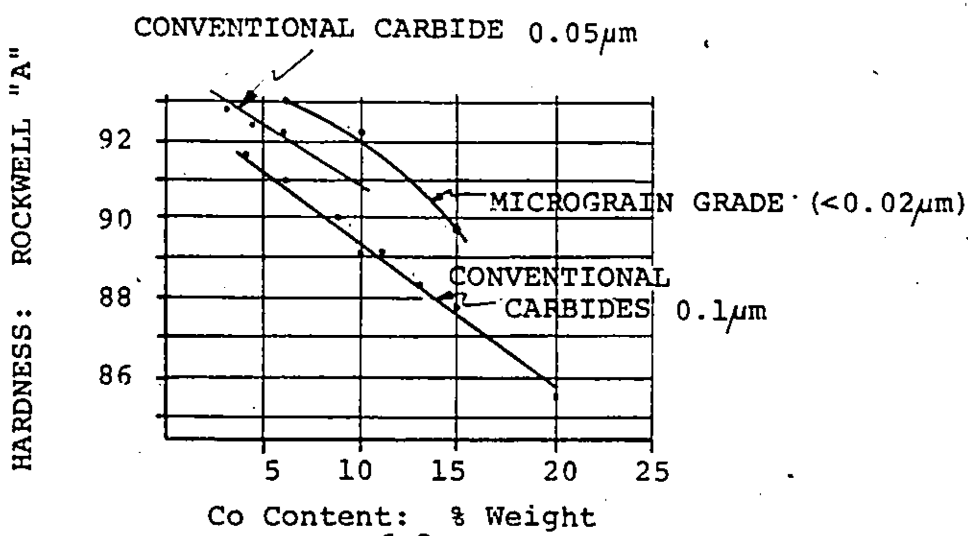


FIG. 6.2

Effect of cobalt content on Rockwell "A" hardness of conventional and micrograin carbides.
(reference [24])

MATERIAL ----------: CAST IRON 250 BHN
DEPTH -------------: 4 mm
FEED --------------: 0.97 mm/rev
TOOL LIFE CRITERION: FLANK WEAR 0.4 mm

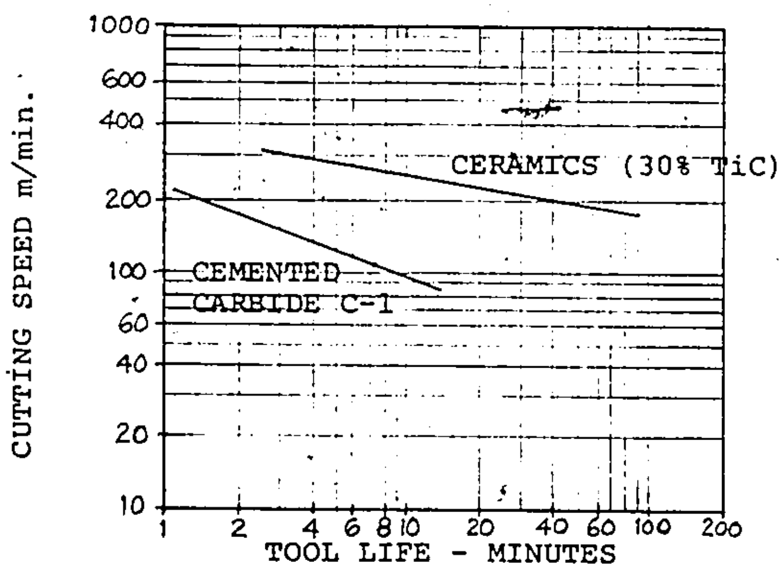


FIG. 6.3

TOOL LIFE CURVES [25]

MATERIAL: AISI 1045, 180 BHN
FEED: 0.25mm/r DEPTH: 3.2mm
TOOL LIFE: 0.25mm FLANK WEAR

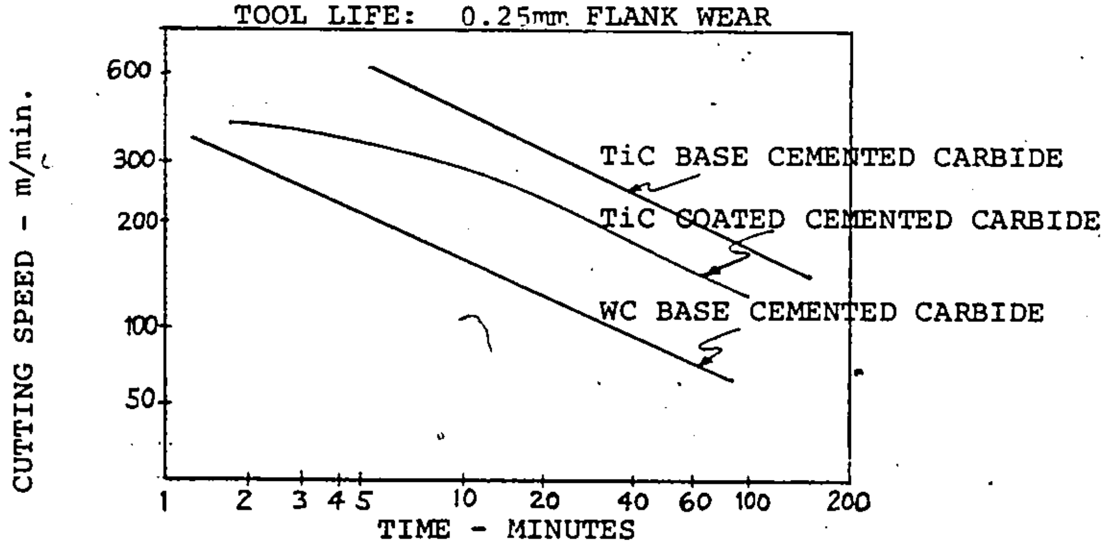
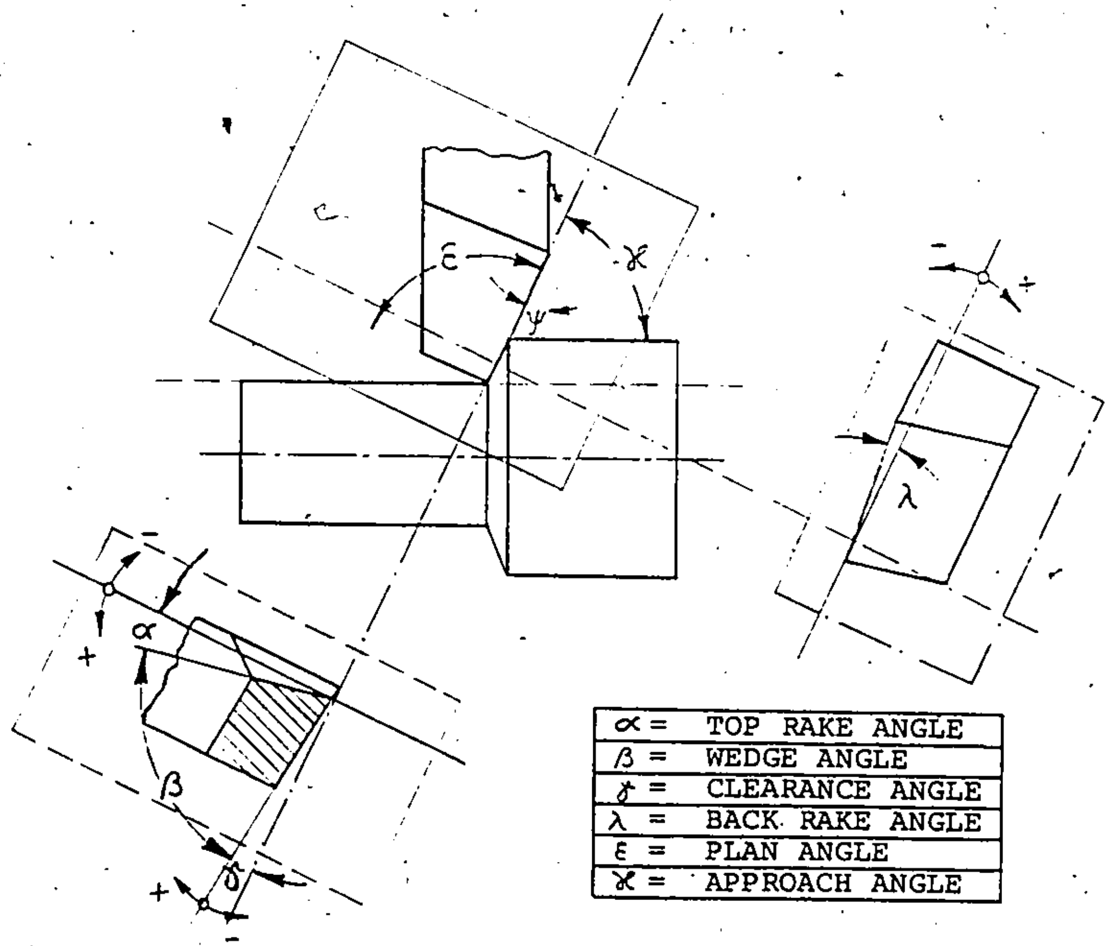


FIG. 6.4

TOOL LIFE CURVES

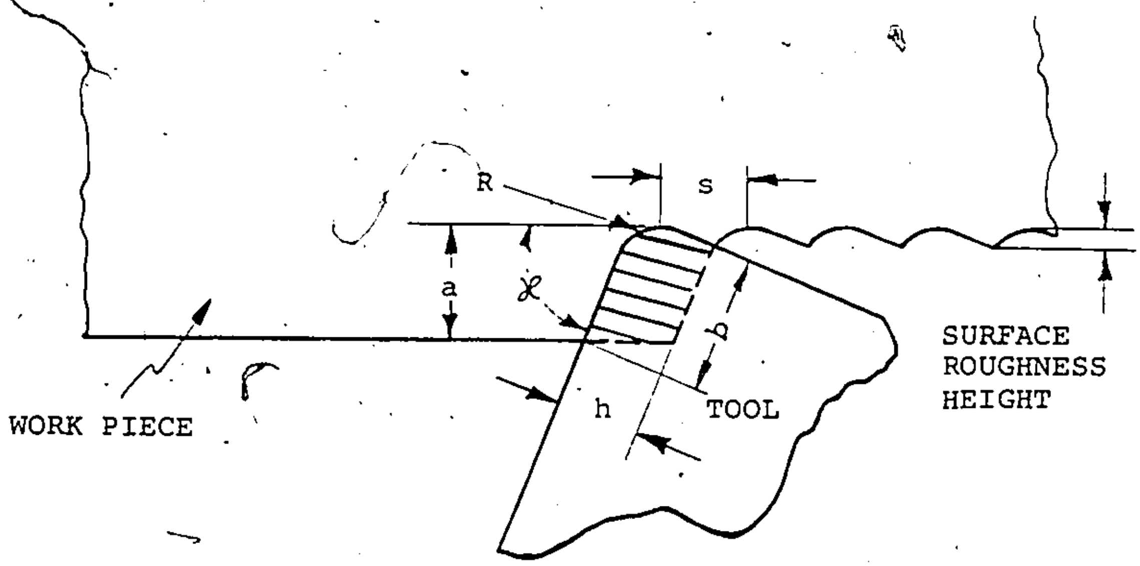
(reference [25])



α	=	TOP RAKE ANGLE
β	=	WEDGE ANGLE
γ	=	CLEARANCE ANGLE
λ	=	BACK RAKE ANGLE
ε	=	PLAN ANGLE
$\varkappa$	=	APPROACH ANGLE

FIGURE 6.5

CUTTING EDGE ANGLES



$\varkappa$ - LARGE FOR CONVENTIONAL STEEL MACHINING

$\varkappa$ - SMALL, TYPICAL FOR ROLL TURNING

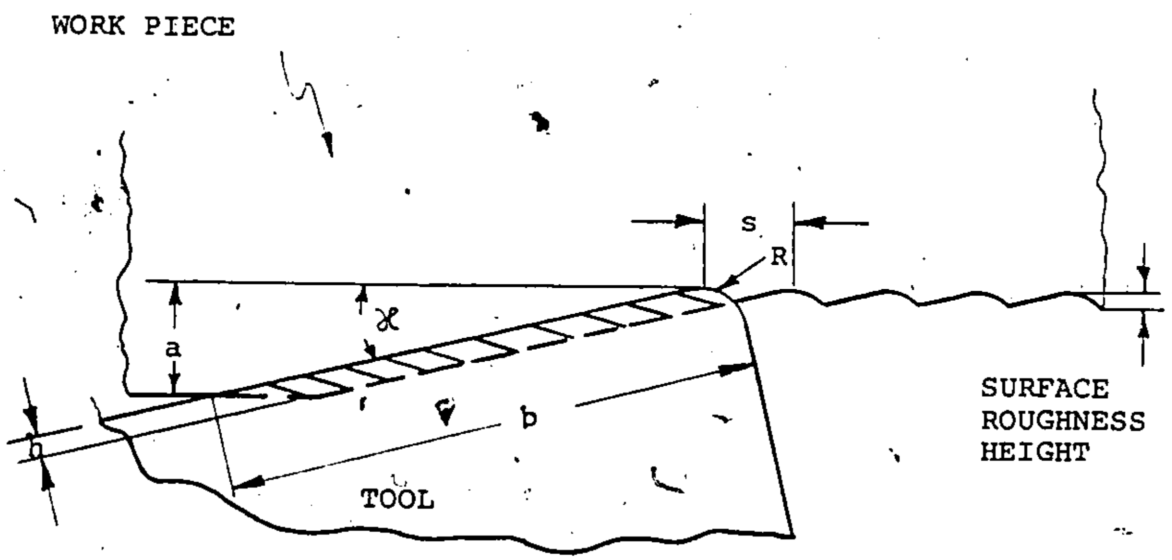
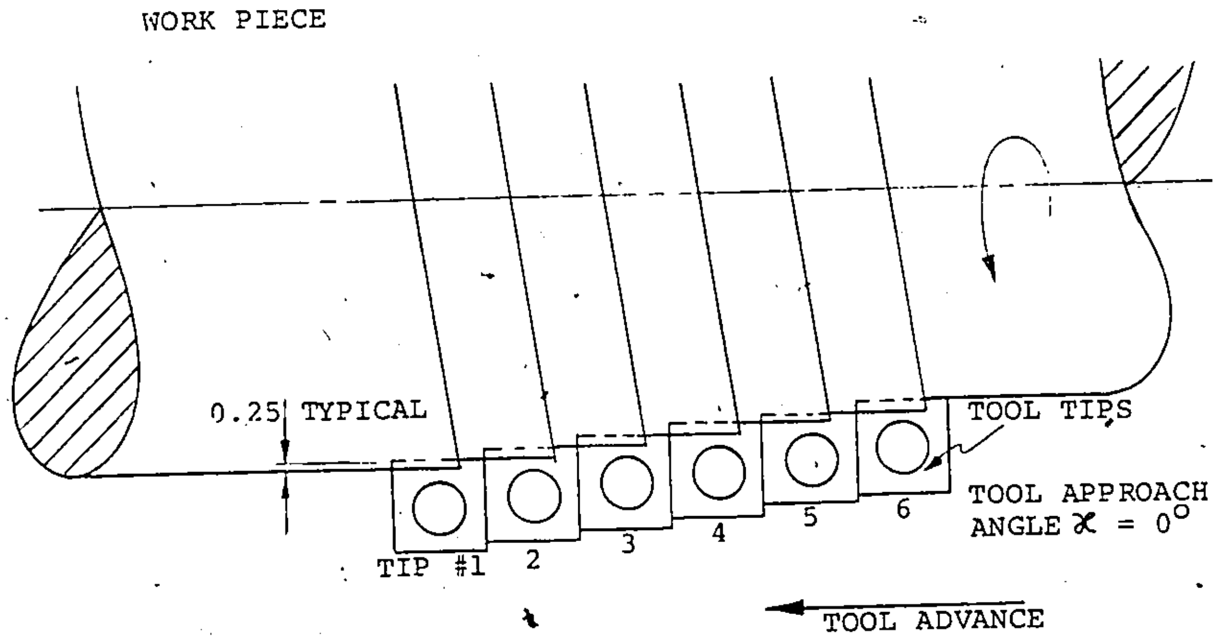


FIG. 6.6

RELATIONSHIP BETWEEN APPROACH ANGLE '$\varkappa$' AND CHIP THICKNESS 'h' MAINTAINING EQUAL FEEDS "s" AND DEPTH OF CUT "a"



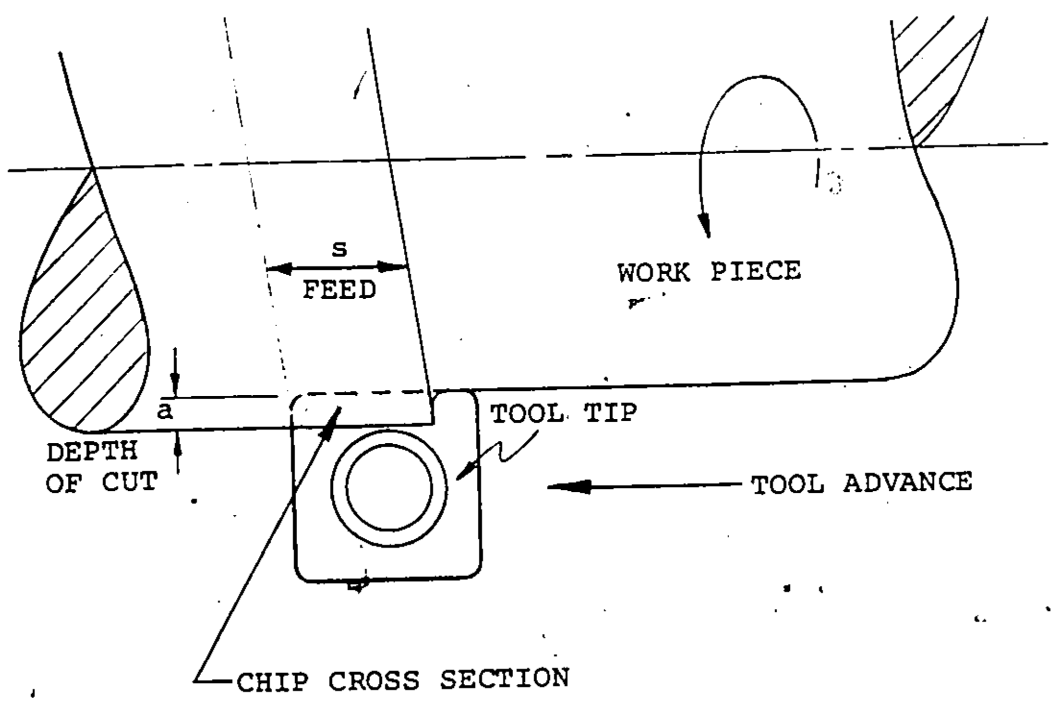
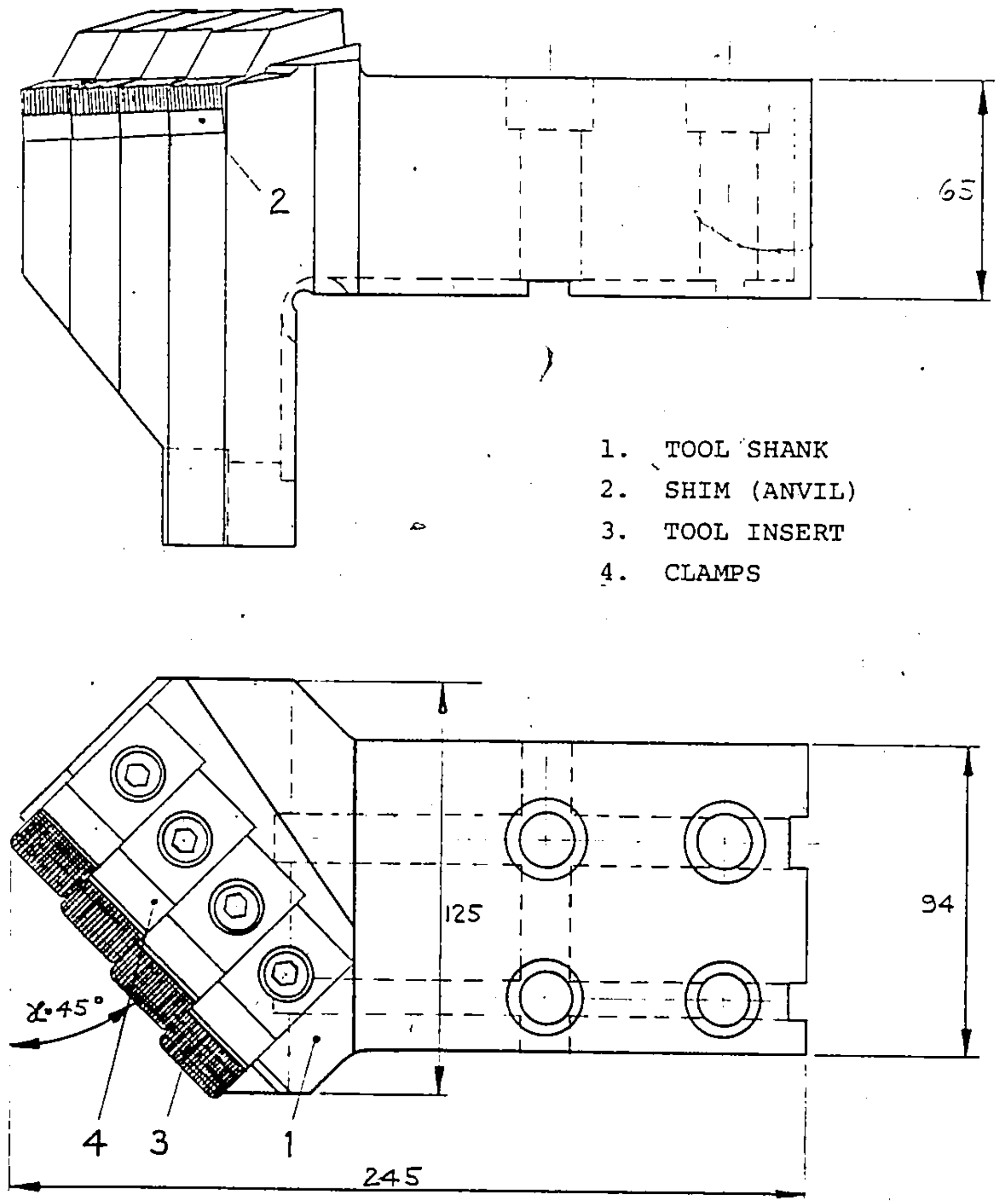


FIG. 6.7

CUTTING PERFORMANCE WITH $\varkappa = 0^{\circ}$ APPROACH ANGLE



ALL DIMENSIONS IN MILLIMETERS

FIG. 6.8

TURNING TOOL FOR ROUGHING CUTS

(SITZMANN UND HEINLEIN, NÜRNBERG)

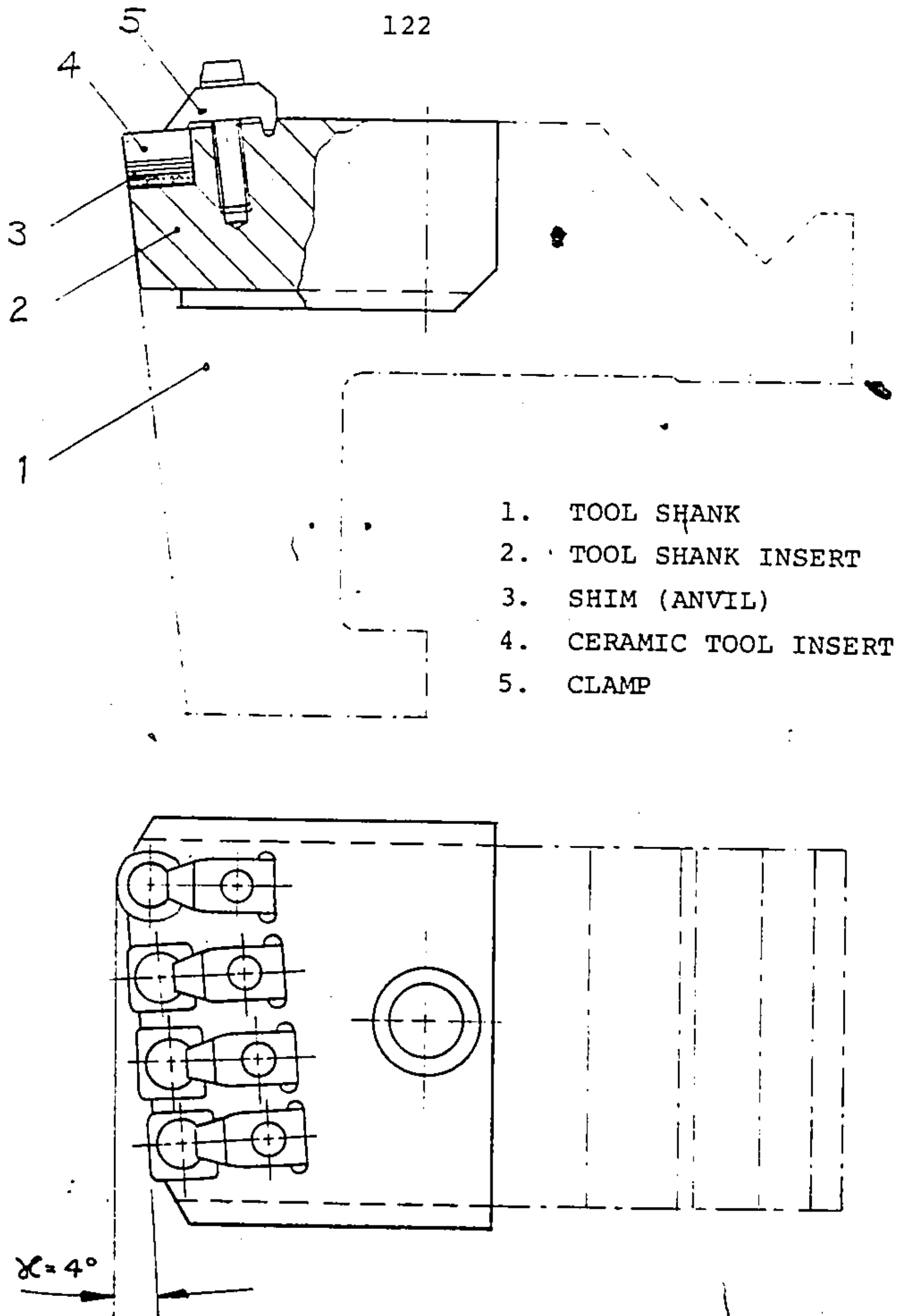


FIG. 6.9

TURNING TOOL FOR FINISHING CUTS

(SITZMANN UND HEINLEIN, NÜRNBERG)

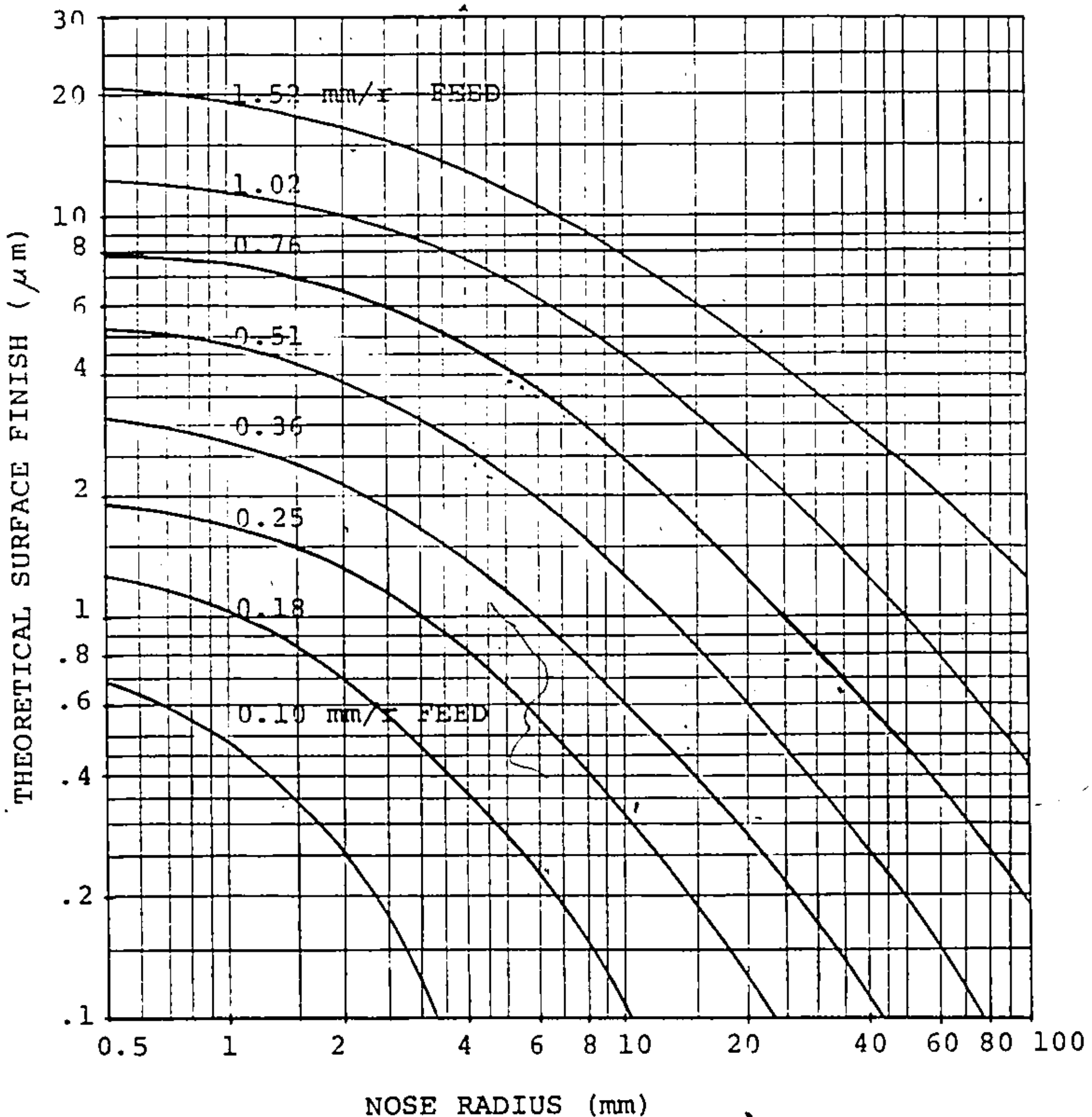
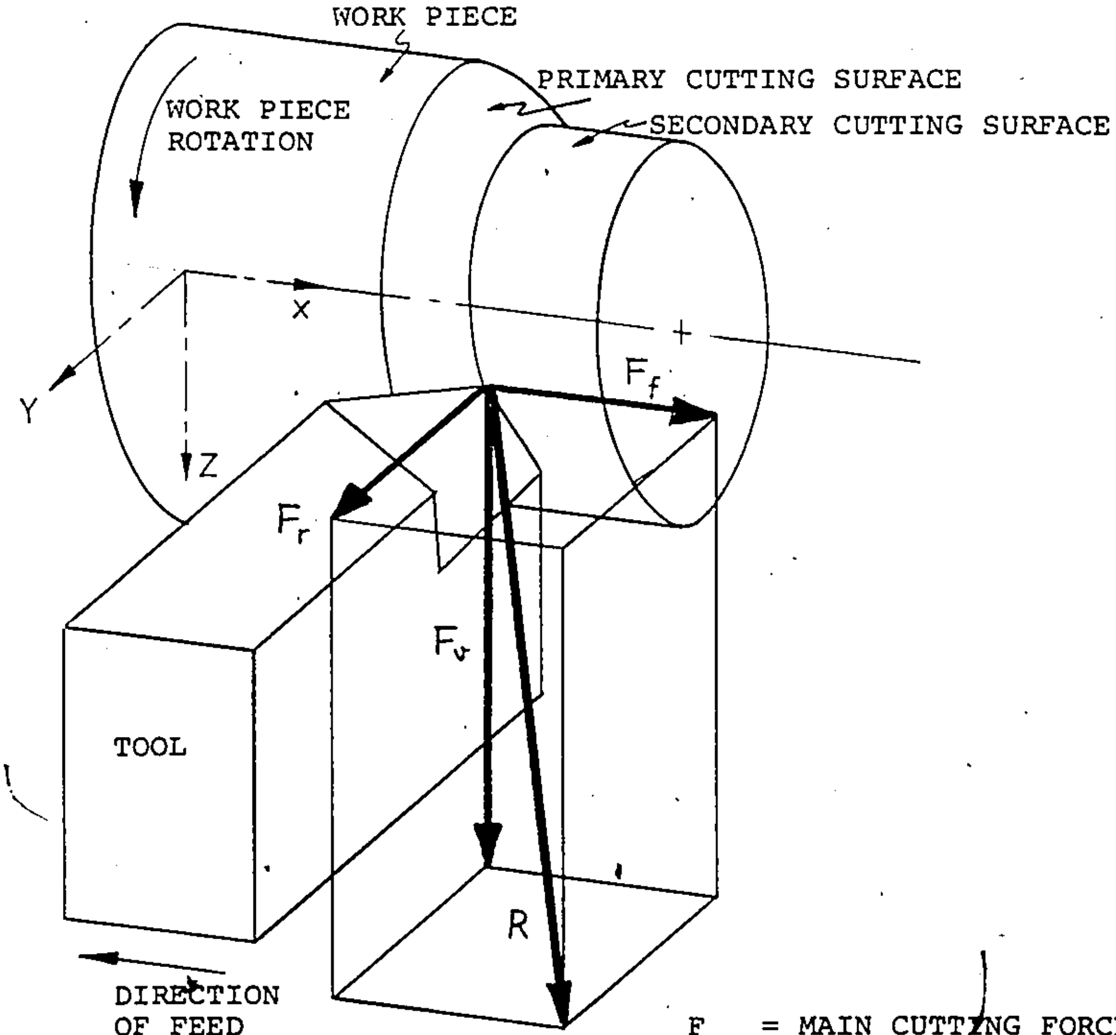


FIGURE 6.10

SURFACE FINISH - FUNCTION OF TOOL NOSE RADIUS AND FEED

(from reference [19])



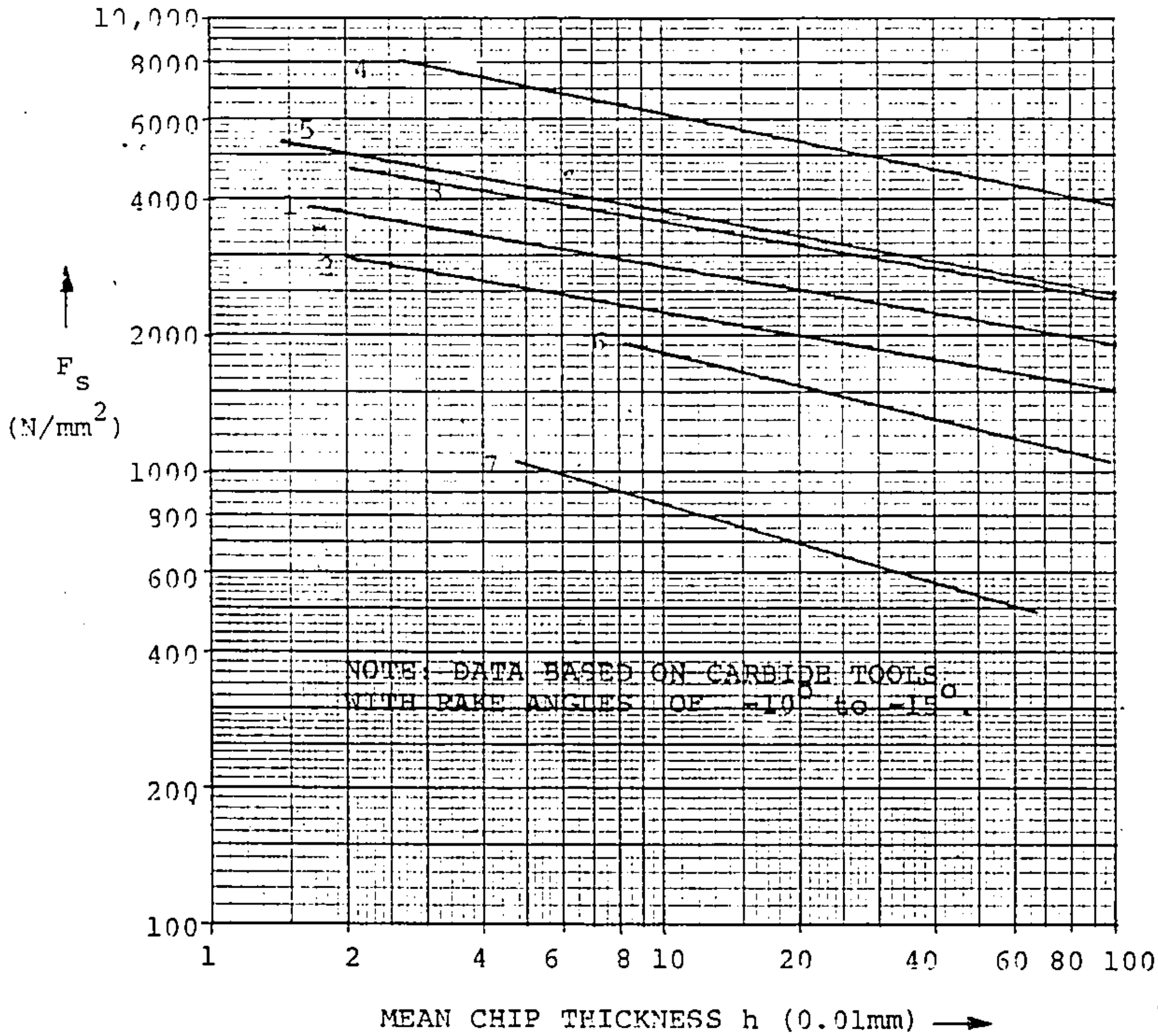
F_v = MAIN CUTTING FORCE, DIRECTED TO PRIMARY VELOCITY MOTION.

F_r = RADIAL CUTTING FORCE.

F_f = CUTTING FORCE IN FEED DIRECTION.

FIG. 6.11

CUTTING FORCES AND DIRECTIONS



1. Forged Alloyed Steel, 830 MPa tensile, 50 Shore "C".
2. Cast Alloyed Steel, 620 MPa tensile, 40-50 Shore "C".
3. Forged Alloyed Steel, 1100MPa tensile, 60 Shore "C".
4. Forged Alloyed Steel, 1580 MPa tensile, 60 Shore "C".
5. Chilled Cast Iron, 75 Shore "C".
6. Cast Iron, HBN 200.
7. Aluminum Alloy.

FIG. 6.12

SPECIFIC CUTTING FORCE DIAGRAM

(from reference [36], [37], [38], [39])

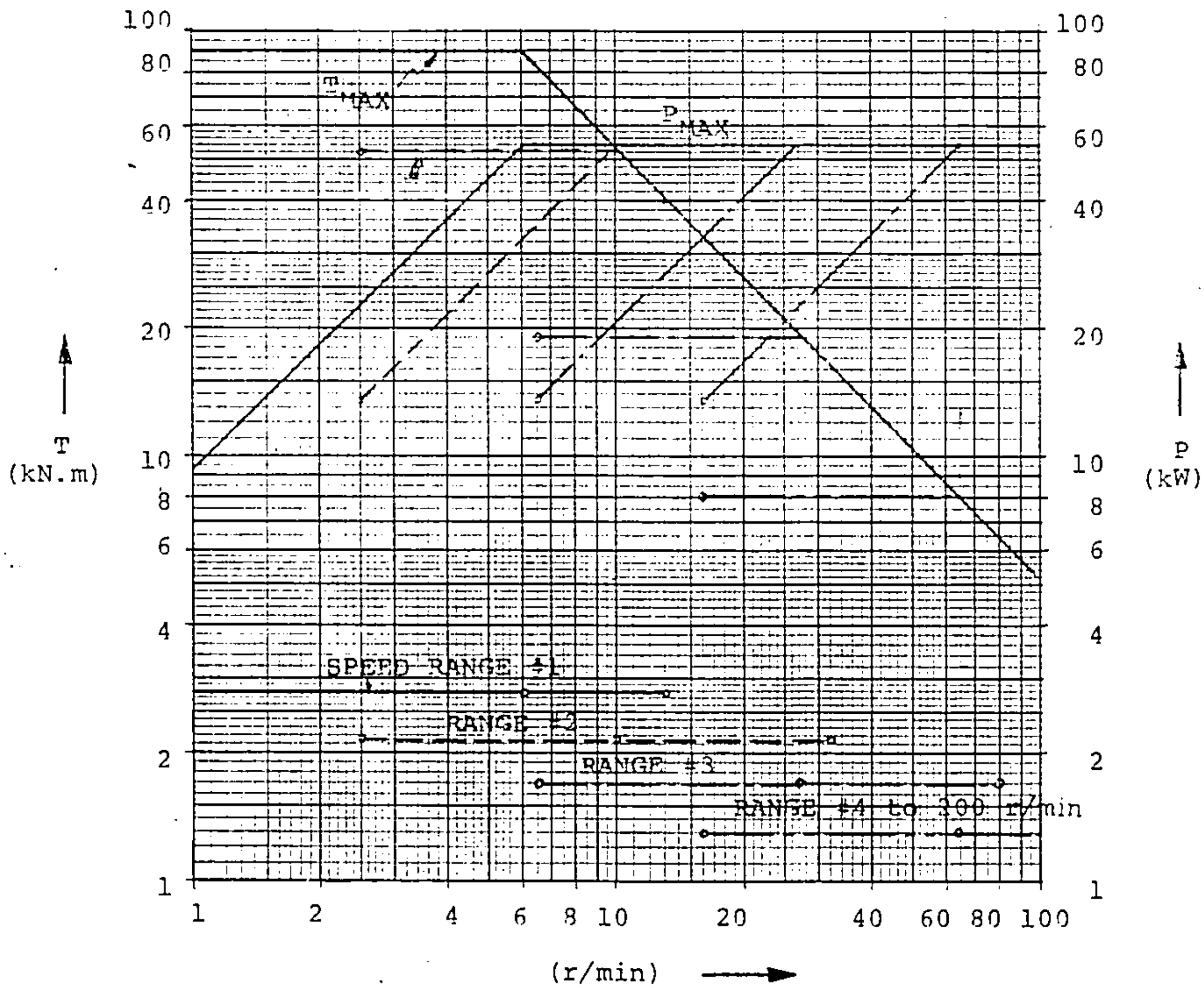


FIG. 6.13

SPEED, POWER, TORQUE DIAGRAM

(from reference [43])

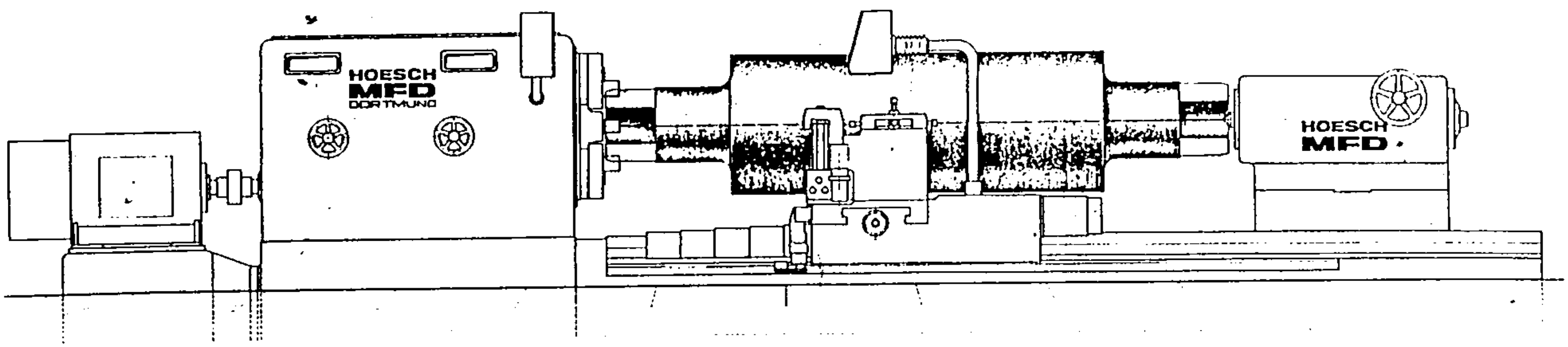


FIG. 7.0

ROLL TURNING LATHE

MFD, MASCHINENFABRIK DEUTSCHLAND

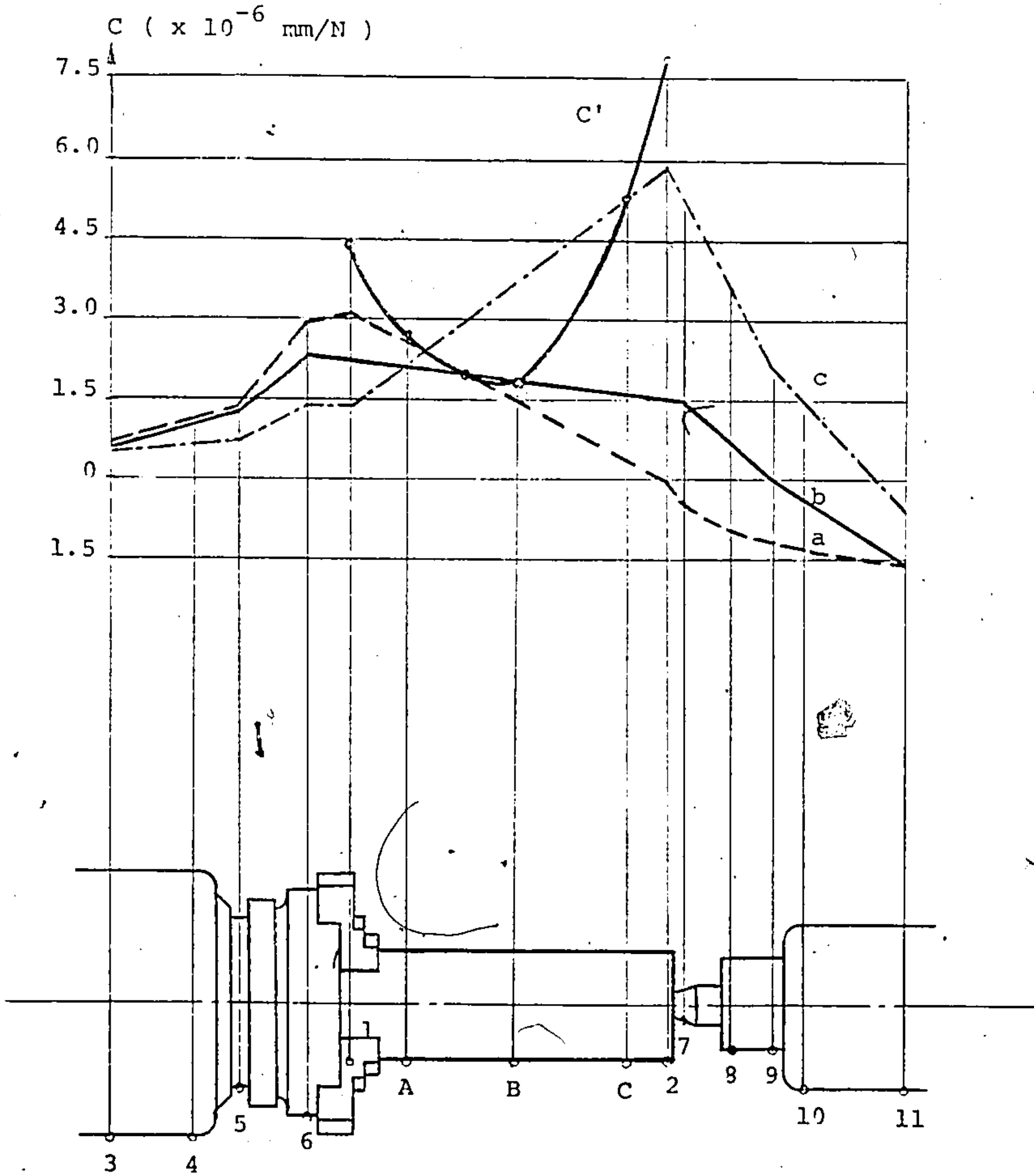


FIG. 7.1.

Resulting compliance C' for workpiece clamped in chuck and centre.

(from F. Koenigsberger and J. Tlusty[35])

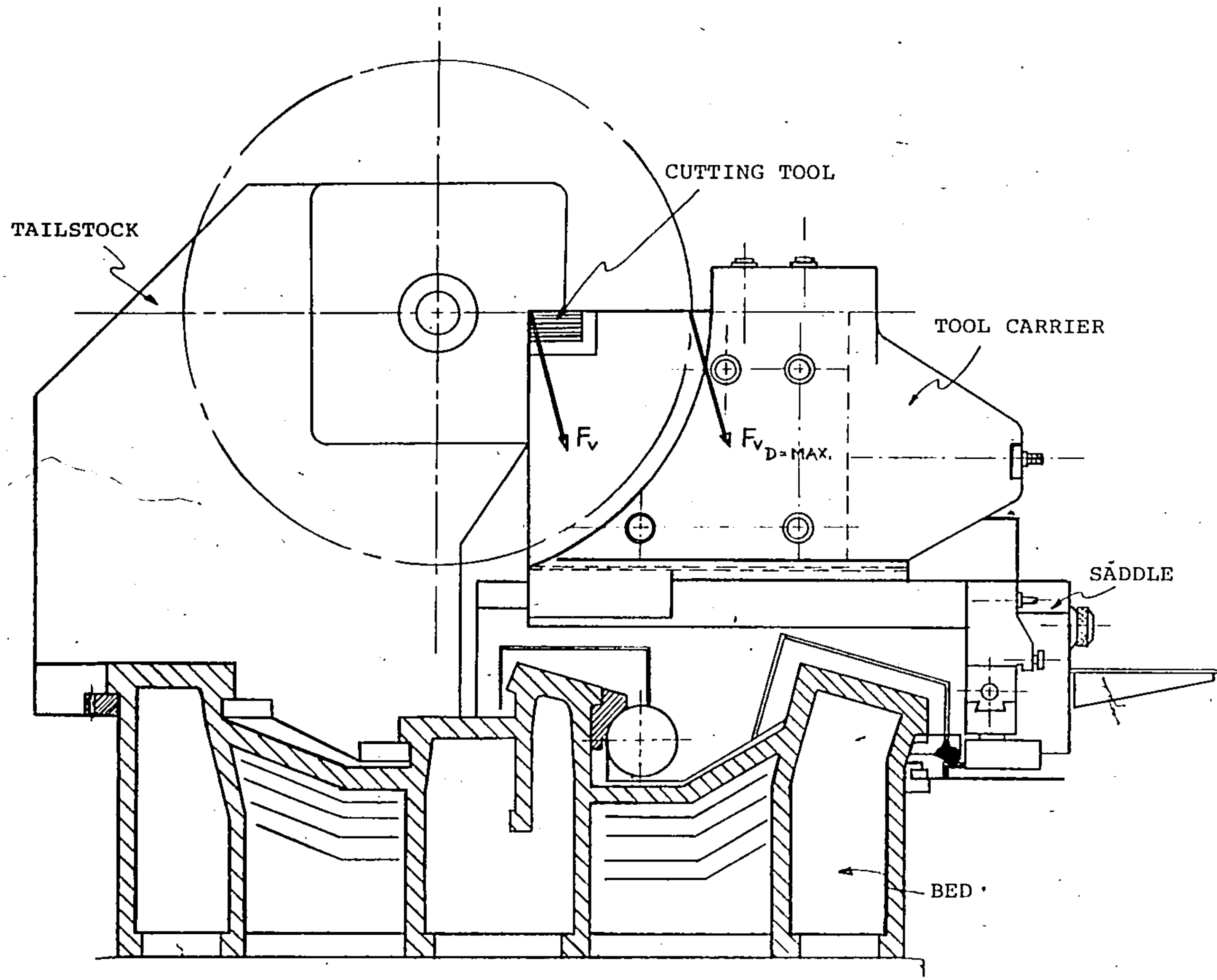


FIGURE 7.2

ROLL TURNING LATHE CROSS SECTION
MFD, MASCHINENFABRIK DEUTSCHLAND

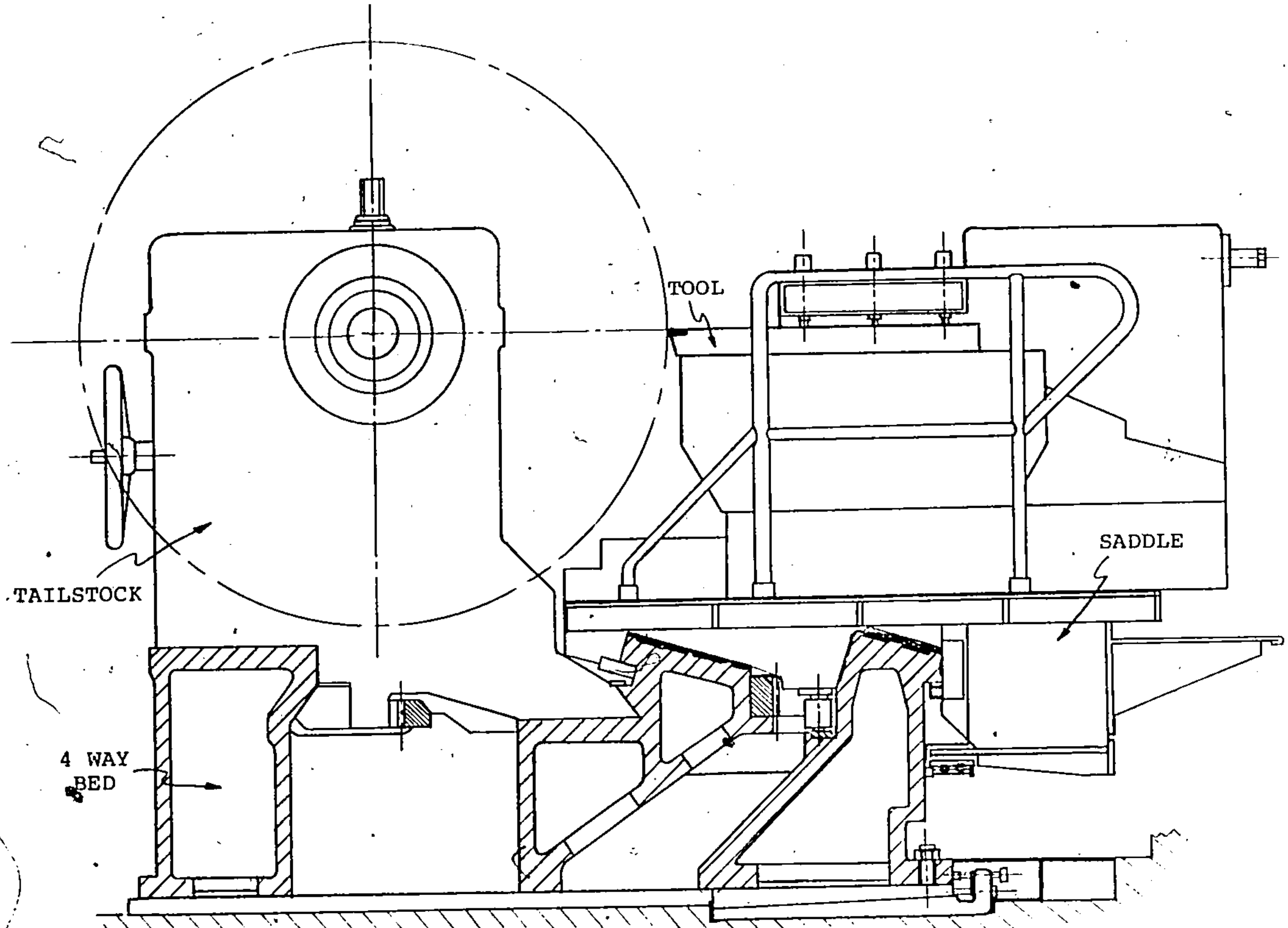
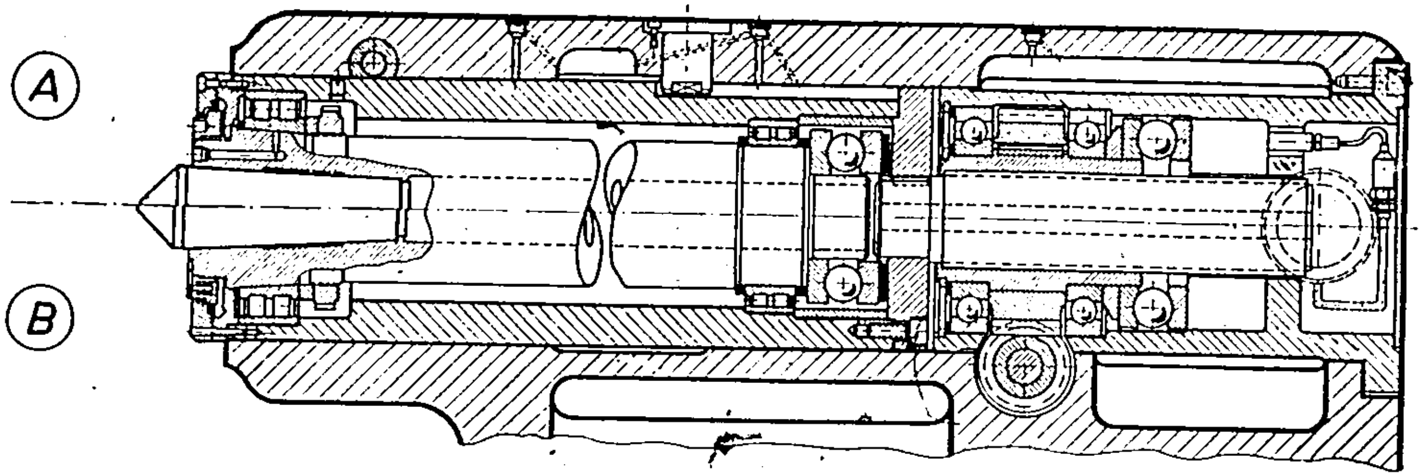


FIGURE 7.3

ROLL TURNING LATHE CROSS SECTION
MASCHINENFABRIK HERKULES



(A) CENTER UNDER LOAD

(B) CENTER FREE FROM LOAD

FIG. 7.4

CROSS SECTION THROUGH TAILSTOCK

HEYLIGENSTAEDT WERKZEUGMASCHINENFABRIK

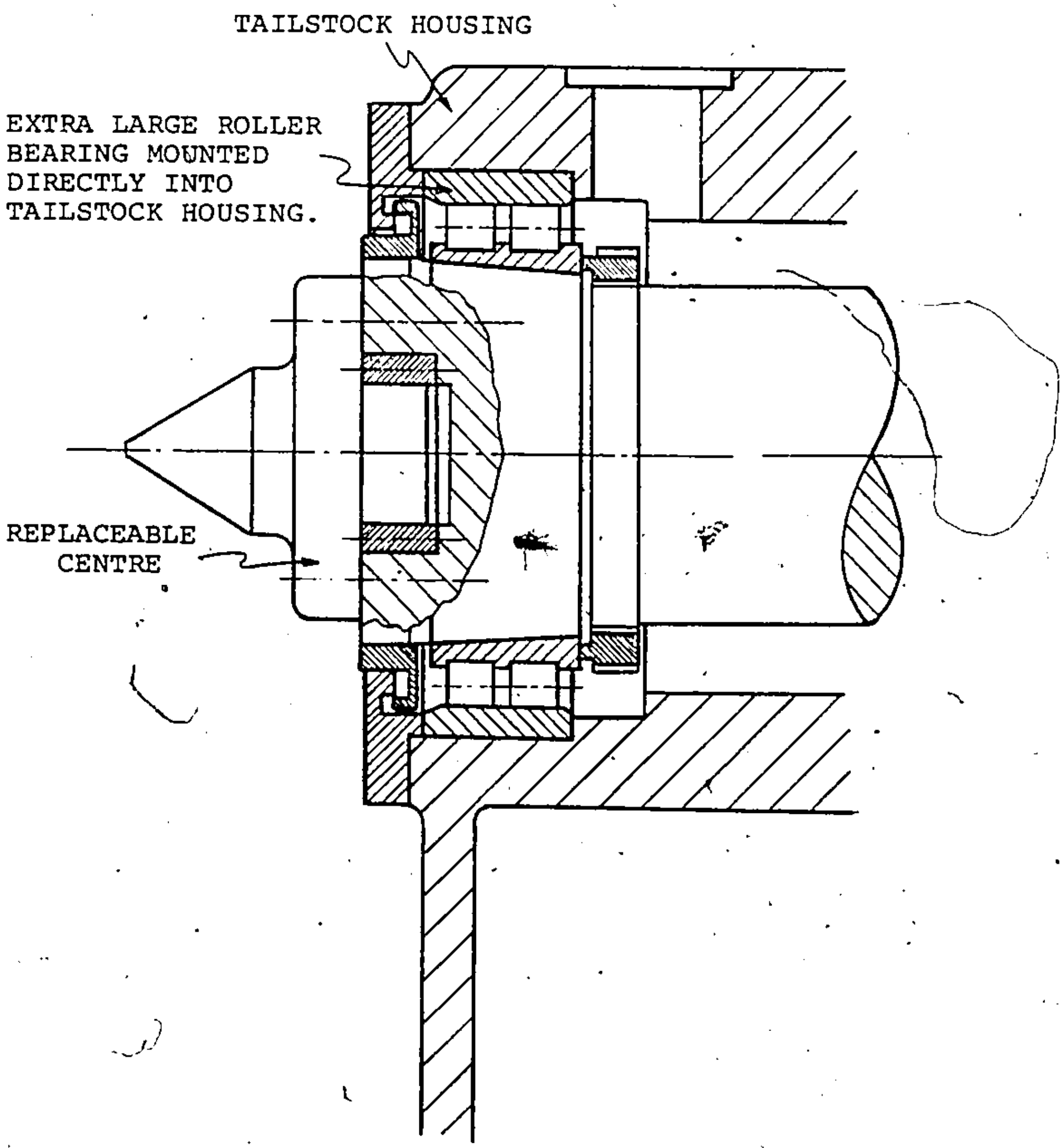


FIGURE 7.5

TAILSTOCK DESIGN

MASCHINENFABRIK HERKULES

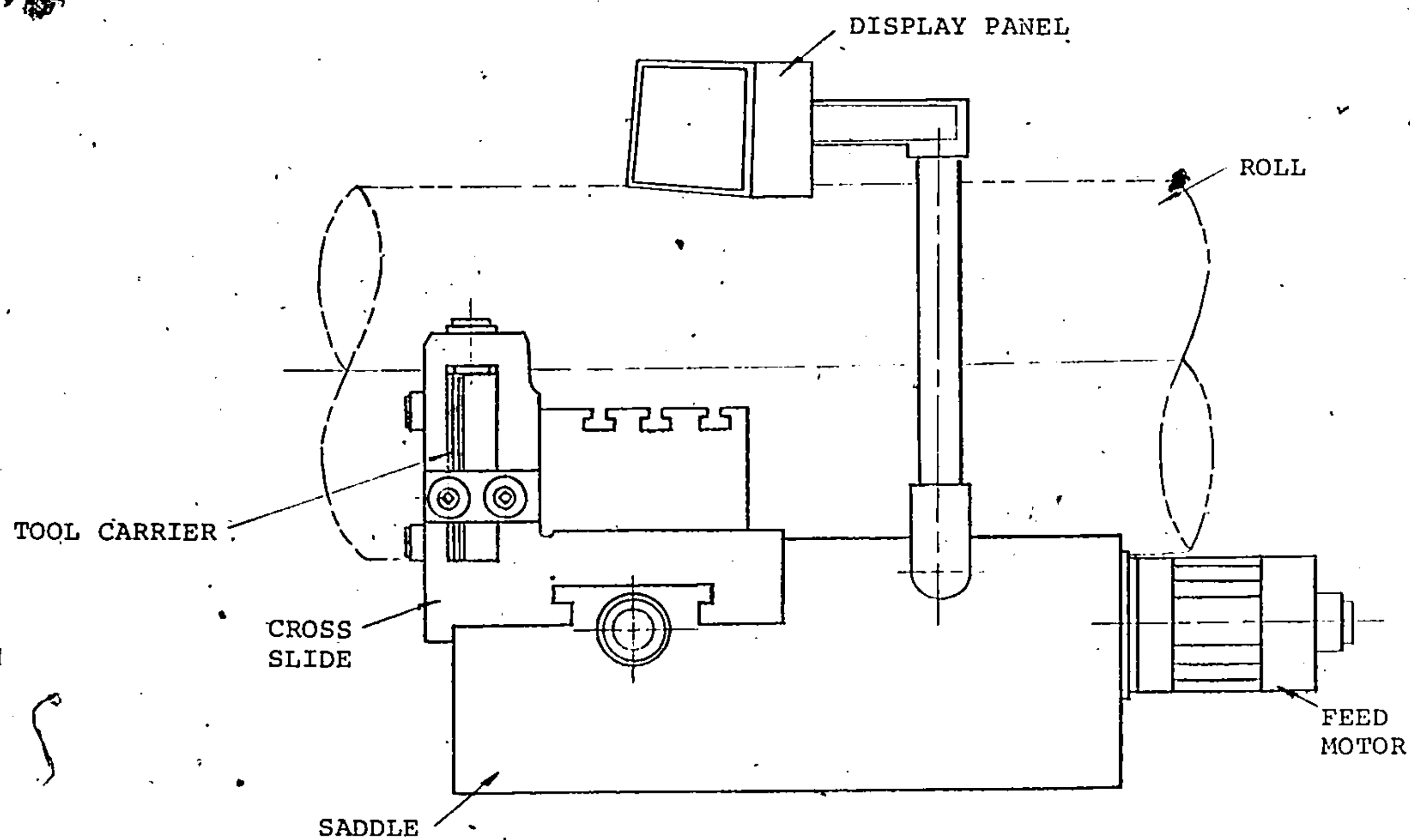


FIGURE 7.6

ROLL TURNING LATHE

CROSS SLIDE AND TOOL CARRIER DETAIL

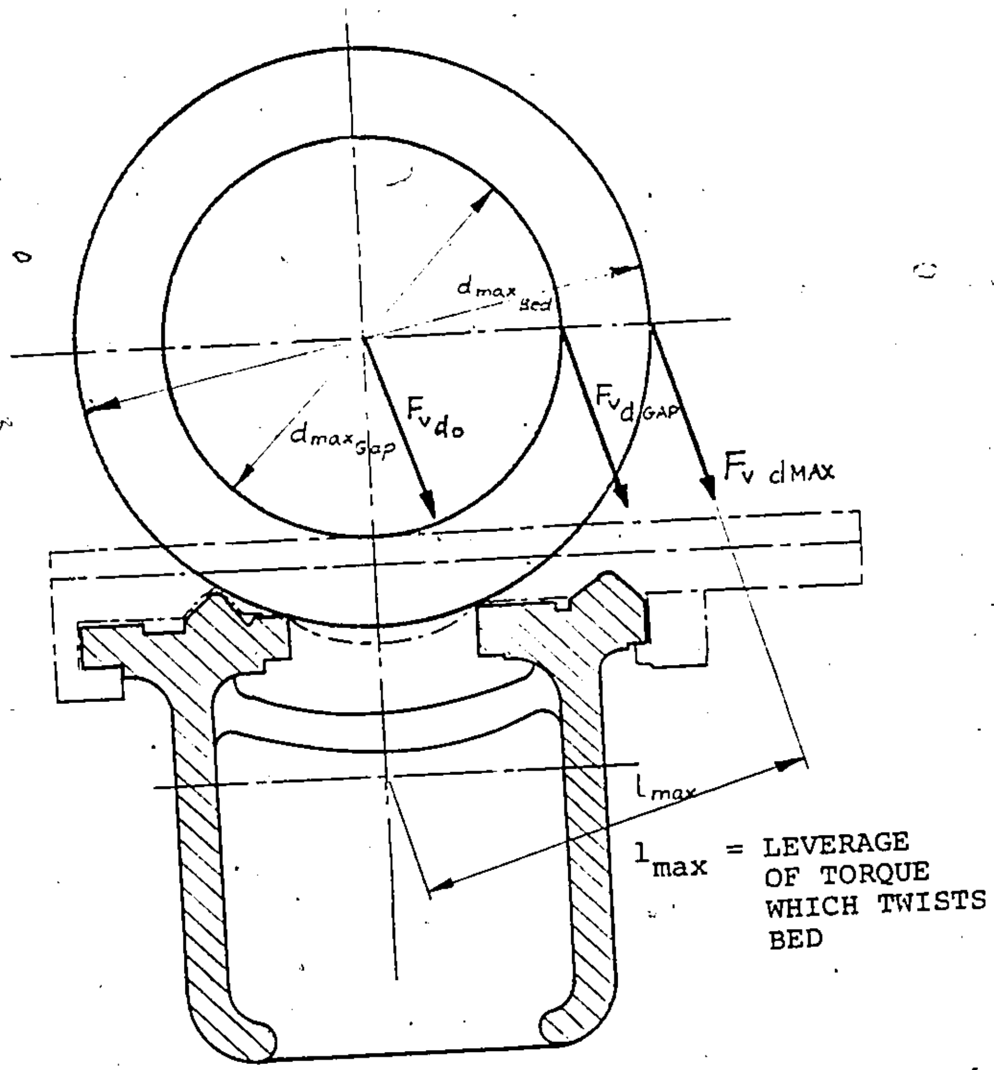


FIGURE 7.7

LOADING OF ENGINE LATHE BED DUE TO CUTTING FORCES

(from reference [39])