Chapter 28

ROLLING FLAT AND SHAPED WIRE

The Manufacturing Process of Rolling – Basic Definitions

Rolling is the technical process of transforming the cross section of a feed stock that passes through a set of rotationally symmetric tools called rolls. Besides shape, the rolling process also changes characteristics of the processed material such as strength, microstructure, and surface.

The process of rolling is mainly used for either ferrous or nonferrous metal stock and is classified into cold, warm, and hot rolling of wire or sheet. This chapter primarily covers the cold rolling of flat and shaped wires.

Flattening as the basic rolling operation for sheet or wire uses two cylindrical rolls with parallel axes (see Fig. 1). If the rolls are designed with a profile groove, the material can be shape rolled. Rod-type stock, such as wire, can also be shaped using more than two rolls (see Fig. 2).

Those rolls that contact the feed stock are called work rolls. In sheet rolling machines where high rolling forces appear, backup rolls are used to support the work rolls (see Fig. 3). Typically backup rolls are not needed for wire rolling due to relatively low rolling forces.

If none of the rolls on the rolling machine are equipped with a drive, the rolling process is called undriven, or friction driven, because the rolls are indirectly driven by the stock being pulled through. In contrast, driven or power driven rolling machines feature at least one or more driven rolls. These systems can be operated as standalone machines because pulling equipment is not required.
Comparison with Alternative Manufacturing Methods

Slitting

If flat strip is required, it can either be made by rolling round wire or by slitting a wide, flat sheet to multiple strips. Rolling is advantageous for narrow strips, while slitting is limited to strip widths wider than 5 mm because shearing discs cannot be infinitely narrow. Another limitation for slitting is the length of the produced strip.
Each slit stripe is limited by the length of the coil, whereas round wire rolling leads to virtual endless strips (see Fig. 4).

Also, unlike rolling, the shearing of strips in slitting machines creates burrs and chamfers that are unacceptable in many applications.

![Fig. 3. Sheet mill with small work rolls and three rows of backup rolls.](image)

**Fig. 3. Sheet mill with small work rolls and three rows of backup rolls.**

![Fig. 4. Rolling versus slitting.](image)

**Fig. 4. Rolling versus slitting.**

**Drawing**

For round wire production the use of drawing dies and related machinery is usually more economical, than rolling machines
because the design of capstans is simple and dies with circular shape are inexpensive.

When shapes more complex than simple rounds are needed, rolling is preferably applied because shaped dies are expensive and can’t be refurbished after wear as rolls can be. Another reason for rolling instead of shaping with dies is the characteristic spreading of the rolled material that does not appear in the drawing process. Smaller feedstock sections can be used for shapes characterized by a width-to-thickness ratio value of 2:1 or higher, unlike with the drawing process.

Rolling is the only applicable forming technology for some metal stock because these materials have a micro-structural layout that either breaks during drawing or shows an unsatisfactory surface after passing the die.

Rolling generally creates a better surface quality than drawing because unlike drawing it proceeds without lubrication. As the demand grows for read-to-use wire, the surface preparation used to make the lubricant adhere to the wire surface is becoming unpopular because it creates rough surfaces.

Design Criteria for Wire Rolling Machines

The rolling machine’s design criteria are determined with regard to finished wire requirements such as shape, size, dimensional variation, strength, and production quantity.

Wire Shape and Size

To configure the optimal rolling machine for a final given shape, the first thing to determine is the shape and size of the feed stock. These affect the shape and size of the finished wire and the applicable rolling sequence. The availability of feed stock also has to be considered.

One very important parameter for selecting the appropriate feed stock is the wire’s elongation caused by rolling. The rolling process always reduces the wire’s cross section and—due to volume constancy—increases its length. The rolls force the wire to align to the rolls’ surface geometry in the contact zones between rolls and wire. As a reaction, one portion of the material flows in an orthogonal plane to the wire’s longitudinal axis into those areas that are not bounded by the rolls. This movement is called spreading. Another portion flows parallel to the wire’s longitudinal axis. This movement is called
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**elongation.** The simplest example is the flat rolling of round wire (see Fig. 5), which becomes thinner, wider, and longer by rolling.

![Fig. 5. Thickness reduction, elongation, and spread in the flattening process.](image)

The ratio between spread and elongation is difficult to predict due to the large number of parameters that affect spread. Even though for some basic forming processes approximate calculation formulas are available, a precise calculation is not possible so far.

The following relations can be used to predict and influence the degree of elongation. It has been theoretically and practically proven that spread is higher when:

- The ratio of roll diameter to wire size is higher
- The friction coefficient between roll and wire is higher (rough roll surface, rough wire surface, low grease content in lubricant)
- The wire’s tensile strength is higher
- The width of the feed stock is smaller
- The degree of forming per step is higher
Once the size and shape of the feed stock is determined, the number of rolling steps and the type of rolling machine for each step is decided. This rolling sequence is designed either by experience with similar shapes, reference to literature, or computer-based simulation. At this point only the forming steps are considered without regard to any limitations given by the available machine equipment, wire formability, etc.

**Separating Forces**

Rolling—as any forming process—is based on plastic flow. Therefore, stress, which is higher than the material’s yield strength, has to be applied. During the rolling process the material’s yield strength usually increases by work hardening—especially when cold rolling is used. The average value of yield strength before and after the forming step is used to calculate separating forces. These values can be found in flow curves that are available for most steel grades.

The dimensions and shapes for each forming step are defined in the rolling sequence. These parameters are used to determine the contact zone’s area \( A \) between roll and wire. The separating forces \( F \) that affect each roll and the supporting structure are calculated as the product of this area and the average yield strength \( YS \).

\[
F = YS \times A \quad \text{Eq. (1)}
\]

Because of relative movements between roll and wire surface, which are caused by spread and elongation, the effective separating forces are higher than the theoretical values. The difference is incorporated by introducing a grade of efficiency \( \eta \) into the calculation formula.

\[
F = \frac{YS \times A}{\eta} \quad \text{Eq. (2)}
\]

For some simple forming operations (e.g., flattening without spread limitation, see Fig. 6) the calculation formulas and efficiency grades are provided in the literature.
Eq. (3)

\[ F_{fl} = YS \times l_d \times \frac{b_0 + b_1}{2} \times \frac{1}{\eta} \]

where:  
- \( F_{fl} \) = Separating force for flattening  
- \( YS \) = Average yield strength  
- \( b_0 \) = Width before rolling  
- \( b_1 \) = Width after rolling  
- \( \eta \) = Grade of efficiency

Eq. (4)

\[ l_d = \sqrt{\frac{d \times (h_0 - h_1)}{2}} \]

where:  
- \( l_d \) = Contact length  
- \( d \) = Roll diameter  
- \( h_0 \) = Thickness before rolling  
- \( h_1 \) = Thickness after rolling
It is more difficult to calculate complex processes such as shape rolling with four rolls. Recently the simulation with finite element methods (FEM) can predict the forces accurately. However, these methods require expensive, sophisticated computer hard- and software and are, therefore, seldom used.

Separating force is defined by the size of the contact zone area. Therefore, small roll diameters generate smaller separating forces than larger roll diameters in a given rolling process. In strip rolling mills, rolls with small diameters are used to reduce forces. As these small rolls tend to bend, backup rolls are used for support (see Fig. 3). In wire mills, the separating forces are lower due to smaller width of the rolled material and support rolls are usually not found.

After identifying the separating force, a suitable rolling machine is selected based on:

- the machine’s break load and the static bearing capacity of the used roll bearings
- the lifetime of the bearings. This is calculated according to the required production speed. Usually, the nominal lifetime is 10,000 hours; however, in multi-roll machines (e.g., turks-heads) due to limited installation space for bearings the nominal lifetime sometimes reaches less than 2,000 hours only.
- the elastic deformation of the machine caused by the separating forces. This can only be calculated if the machine’s spring constant, which represents the machine’s stiffness, is known. The higher the requirements on the dimensional constancy of the rolled wires are, the stiffer the machine should be. Alternating separating forces—caused by variations of the feed stock’s yield strength or its dimensions—will result in alternating dimensions after rolling. High stiffness makes the machine less sensible for variations of the separation force.

The maximum specific surface pressure is the criterion for selecting the material grade of the roll, not the separating force. The roll’s yield strength must be higher than the wire’s yield strength. For wires with yield strengths up to 1000 to 1200 N/mm² the use of hardened conventional tool steels is sufficient. However wear is lower if the rolls are made from tungsten carbide materials.
For higher grade wires the use of tool steel rolls is not possible because the rolls will break due to the specific loads applied. These wires demand tungsten carbide rolls. Alternatives can be powder metallurgical materials or, to a lesser extent, ceramic, which is seldom used because it was introduced recently into rolling technique.

**Torque and Power to Drive the Rolls**

To perform the rolling operation, it is necessary to drive the rolls. The required torque can either be created by connecting the rolls to a motor (power-driven machine) or by applying a pulling force to the wire (friction-driven machine).

Rolling machines with a combination of driven and undriven rolls, such as four-roll designs (also called turks heads) with two driven and two undriven rolls, don’t need external wire-pulling equipment. In that case, the driven rolls drive the wire that subsequently moves the undriven rolls.

For the torque calculation the values of separating force ($F$) and the distance ($a$) between the connecting line of roll centers and the balance point of the separating force are multiplied (see Fig. 7).

$$M = 2x F x a$$

Eq. (5)

where:  
$M$ = Driving torque  
$F$ = Separating force  
$a$ = distance from centerline to the balance point of the separating force

The tangential force for each roll is calculated by dividing the torque by the half-roll diameter. The pulling force needed for friction driven machines is the sum of the tangential forces of all rolls.

$$F_t = \frac{M}{2} \times \frac{2}{d} \times 2 = 2x \frac{M}{d}$$

Eq. (6)

where:  
$F_t$ = Tangential force
The power \( P \) needed for the rolling process is the product of the sum of the tangential forces of all rolls and the rolling speed \( v \).

\[
P = F_i \times v \quad \text{Eq. (7)}
\]

where: \( P \) = Driving power
\( v \) = Rolling speed

**Friction Between Wire and Rolls**

Driven rolls basically have the ability to draw the wire into the gap between the rolls and feed it through. This feature is limited by the contact angle and the friction coefficient between roll and wire. With a given height reduction and roll diameter the contact angle \( \alpha \) between roll and wire can be calculated as:

\[
sin (\alpha) = \frac{l_d \times 2}{d} \quad \text{Eq. (8)}
\]
For feeding in the wire by driving the rolls, the required friction coefficient is:

\[ \mu_{\text{feed}} \geq \tan(\alpha) \quad \text{Eq. (9)} \]

To transport the wire through the rolls by driving them, the required friction coefficient is smaller:

\[ \mu_{\text{trans}} \geq \tan\left(\frac{\alpha}{2}\right) \quad \text{Eq. (10)} \]

These formulas show why, even though a specific rolling process is operating successfully, the wire feeding process might not work at all. To ease the wire feeding process, the contact angle may be reduced by opening the rolls or by pointing the wire. Another possibility is to increase the friction coefficient by switching off the lubrication of the roll surface, degreasing the front end of the wire, or roughening the rolls.

Practice has shown and theory can explain that the friction coefficient depends not only on the surface of wire and rolls and the character of the lubricant but also on the rolling speed. For this reason the maximum degree of forming is reached at low speeds. If high production speeds are required, usually more forming steps are applied to avoid wire transportation problems.

If the actual friction coefficient is even smaller than \( \mu_{\text{trans}} \), the wire will not move, even though the rolls are rotating. During this standstill, the lubricant between wire and rolls escapes, the friction coefficient increases, and the wire eventually starts moving again.

This alternating start-stop process affects the quality of the rolled wire. The wire surface is damaged and dimensions will vary because wire tension between the rolling machines is not constant. Moreover, the escape of lubricant during the standstill of the wire creates either adhesive or abrasive wear on the rolls’ surfaces.

During the rolling process the cross-sectional area of the wire is reduced and the wire is elongated. This means that the wire is accelerated on its way through the contact zone. As the roll’s surface moves with constant speed, therefore, a speed difference exists between wire and roll. It can be shown that the wire speed is slower
at the entrance to the contact zone and is faster than the roll surface at the exit. There is only one point at which the speed of the wire is the same as the speed of the roll.

The speed difference between roll and wire surface is a characteristic of the rolling processes and does not create wear as long as the lubricant separates the surfaces of wire and rolls. For this reason rolling without lubrication always creates wear due to relative motion between contacting surfaces.

The above considerations show that a non-slip rolling process, promoted by some rolling machine manufacturers, does not exist. Any speed synchronization between roll stands can only minimize speed differences between rolls and wire.

Wire Temperature

During the rolling process a forming energy is applied to the wire, and this energy is almost entirely converted into heat, elevating both the temperature of the wire and the rolls. The degree of heating is related to the yield strength of the wire and its heat capacity as follows:

- High tensile wires providing high yield strengths get warmer than those with low yield strength because they require more energy for forming.
- If the same forming energy is applied, wires with low heat capacity get warmer than those with high heat capacity.

The heating of the wire caused by rolling is independent of the rolling speed, which is—at first sight—surprising, because the practical work with rolling machines shows that the wire temperature rises after rolling with the increase of line speed. The explanation for this correlation between wire temperature and line speed is that, contrary to the heating by rolling, the subsequent cooling is time-dependant. The longer the cooling processes are applied, the lower are the final wire temperatures.

Cooling is mainly done by heat transduction from wire into rolls and cooling lubricant. As the calculation of rolling forces and the related applied power is already difficult, the calculation of wire temperatures is even more challenging. Especially the cooling by lubricant contact, as a complex heat transferring flow process is influenced by countless parameters. Even FEM-based calculations can only provide approximate results.
Other than setup time, the most important machine parameter is production speed. To reach the required wire properties at an economic line speed, the wire temperature must be kept below critical values because of the following:

- The yield strength of wire and the related separating forces drop with high temperature. Because of the machine’s elasticity this leads to dimensional deviations.
- The degree of elongation changes with variations of yield strength and friction coefficient. This again leads to dimensional deviations.
- Lubricant properties can change causing differences in wire surface quality.
- The mechanical properties of the final wire can be different when rolled at different temperatures.
- Roll dimensions can change due to heat expansion. As a result the wire dimensions can vary.
- If the final wire is coiled on spools in warm conditions, the cooling is accompanied by shrinkage. This generates high loads resulting in surface damage and geometric failures, especially on the inner windings of the coiled wire. To avoid this, maintain coiling temperatures below 60 to 70ºC.

Effective wire cooling is necessary on high-performance wiredrawing lines because of increased production speeds, accuracy demands, or large per-step reductions. This can be achieved by:

- external cooling of rolls and wire in the contact zone by spraying cooling lubricant
- internal roll cooling with either lubricant or coolant
- dip-cooling of the wire in special basins filled with coolant located after each rolling step. Ideally the wire exits the basin chilled to the coolant’s temperature to avoid heat accumulation from one rolling step to the next.
- use of a coolant with high heat capacity: Water (and water-oil-emulsion) is much more efficient than oil.
- controlling the coolant’s temperature by a re-cooling system

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As a machine typically cools to below the production temperature during standstill-times, such as setup or weekends, high precision lines usually are prepared for production by preheating the rolls and the coolant to working temperature prior to the start of production. Machines with lower production output typically do not require special measures to reduce wire temperature.

**Wire Formability**

At the end of the wire shape and size section, a reference was made to an occasional limitation of the rolling sequence by wire formability.

Material forming as it is applied by the cold rolling process is only possible if the material is ductile, which means plastically formable without damaging the material’s internal structure. The degree of formability is a material parameter that varies for the different steel grades. Basically the degree of formability decreases as the content of carbon and alloys rises. The maximum degree of formability is often found in flow curves for the given steel grade.

After any warm forming—such as casting, hot rolling or forging—steel is ductile. Any applied force that creates tension beyond the yield point causes plastic flow. During plastic flow the material’s crystal lattice layers are displaced against each other. Defects in the crystal structure interfere with the crystalline motion. The number of movable crystal layers reduces and the force required for plastic forming increases. Finally, all crystals are blocked. No further forming is possible. The material’s character has changed from ductile to brittle. Any further increase of the applied force will result in the material’s breakage.

To provide additional forming capability the crystalline structure must be restored. This is done by a heat treatment called recrystallization annealing. Afterward, the material’s ductility is recovered.

When wire is cold rolled, the degree of deformation over the cross section usually is not uniform. Some portions of the section are formed more than others. In strongly deformed zones, the wire gets brittle and starts cracking while other portions are still ductile. This lack of ductility does not necessarily result in a wire break, but it may create wire defects that are the source for subsequent malfunctions of the final wire product.

A simple example is the flat rolling of round wire feedstock during which the round wire is elongated during the rolling process. The
highest degree of longitudinal deformation is found in the lateral zones where the raw wire’s section is smallest. As a result, the flat wire shows cracks in the corners first if the degree of forming is too high. To avoid this, the degree of forming is reduced and the rolled wire is annealed before further flat rolling. To a certain degree more flattening without annealing is possible by the use of edge rolling between flattening steps to reduce stress in the flat wire’s lateral zones.

Typical Designs of Cold Rolling Machines for Wire

Two-high Rolling Machine

The two-high rolling machine design is the simplest one, providing two rolls with parallel axes usually mounted horizontally. In most cases the rolls are driven but, in combination with capstans, undriven types also are used.

The most common application for two-high rolling machines is flat rolling, often referred to as flattening, in which cylindrical plain rolls are used. By profiling the rolls it is also possible to use the two-high design for rolling shapes, but since the four-roll design has been improved, this application has become less important.

The main advantage of two-high design compared with four-roll design is its higher bearing capacity, which allows higher separating forces, and higher degrees of forming. The basic capacity of turks heads is smaller due to space limitations for the bearings. Therefore, in today’s modern rolling mills, two-high machines are usually found in flattening applications either for flat wire production or for pre-forming wires that are finally shaped in turks heads.

The two-high standard design (see Fig. 8) uses rolls with incorporated bearing journals on both ends. Either taper roller bearings or a combination of radial cylinder bearings and axial needle bearings—often in high precision design—are used. While the bearing housings of the bottom roll are fixed in the machine frame, those of the top roll are joined to a mechanical screw-down system consisting of two gearboxes and a spindle.

Usually the wire widths are multiples smaller than the widths of the rolls. To use the whole roll width the standard two-high design usually provides the possibility to shift the entire stand and thereby use several lanes on the roll surface.
In case of roll change, the universal shafts that drive the rolls must be uncoupled and subsequently roll bearings and bearing housings can be removed as complete units. To reduce machine downtime it is recommended to have a complete second set of units on hand.

The two-high machine designs were improved (see Fig. 9) with regard to productivity and precision of the rolled wires. The roller bearings moved inside the roll body, and the drive is realized by a set of geared wheels. The roll change is quicker, the roll is much stiffer, and the roll body material can be selected with regard to its rolling characteristics only, without limitations such as break restrictions due to bending and torque.

Single horizontal shift of the top and bottom rolls is a characteristic of ideal designs (see Fig. 10) that compensates for the trapezoidal effect which is commonly experienced on standard designs when the rolling lane is changed. Motorization of the horizontal roll shift allows for continuous roll traversing. As a result no wear tracks are created and the regrinding cycles are extended.
Edge Rollers

Edge rollers provide two rolls with parallel axes as do the two-high mills. However, unlike the two-high design, the rolls' axes are vertical. Basically an edge roller (or edger) is a two-high rolling machine that is twisted by 90 degrees. Edger machine design is lighter than two-high machines because of the low-force applications for which it is used, e.g., width adjustment of flat wires between two-high machines or the chamfering of pre-rolled shapes to prevent fins.

Fig. 9. Actual two-high design.

Fig. 10. Roll shift.
Usually edge rolling machines are friction-driven. The wire is pulled through by downstream equipment—mostly driven rolling machines. Only in some cases where tension sensitive materials such as copper are processed, can it be advantageous to use driven edgers.

Edge rolling requires rolls with shaped grooves (see Fig. 11). To reduce set-up times some designs allow the use of several grooves arranged beneath each other that can be adjusted to the wire pass line by vertical roll shifting. Other designs provide a cantilever roll shaft to decrease roll change time. This design, however, is less stiff than a system with bearings on both sides of the rolls.

Fig. 11. Friction-driven edge rolling machine.

Turks Heads

The term *turks head* is often used for all variations of rolling machine designs that feature four rolls with 90 degree displacement to each other. As this general specification can lead to confusion future references in this book will be made to standard or universally designed “profile rolling machines.”

*Standard Profile Rolling Machines.* The design of standard profile rolling machines is based on four rolls (see Fig. 12). The roll axes are positioned in one common plane. The angle between neighboring roll axes is 90 degrees. Usually each roll can be adjusted separately; in the simplest design this is done manually. The roll adjustment operates along a vertical axis to the roll axis and directs through the wire’s pass line. This adjustment axis will be referred to as “radial” adjustment.
Depending on the application, the wire is either pulled through the machine, by a capstan for example (so called undriven or friction-driven type), or the machine itself moves the wire by driven rolls. These driven machines (see Fig. 13) usually have a pair of driven and undriven rolls, because in most profile rolling applications there is a significant difference in rolling force and required torque between the two-roll pairs. The pair of rolls, which does most of the forming, usually is the driven one. Only when shapes with a width to thickness ratio between 1:1 and 1:2 are rolled is the use of four-driven rolls justified.

In general the use of driven profile rolling machines is advantageous compared with undriven machines. The degree of forming is higher and the operation is easier as pointing is not required and unshaped wire is not wasted on a capstan’s drum. For a final calibration step the combination of an undriven profile rolling machine and capstan is beneficial because it enables the operator to do a skin pass with minimal transformation and without the risk of roll slippage.

Producing shaped wires with profile rolling machines requires shaped rolls that are individually designed for each rolling step (see Fig. 14). To reduce the costs, many machine designs provide rolls that are split into a basic roll body (often referred to as a “roll mounting device”) and a mounted ring. The roll mounting device is equipped with bearing and shaft and those parts that are needed to connect the roll to the drive. For a quick machine set-up two sets are beneficial.
When one set is in operation, the second set can be prepared with the shaped rings for the next product.

In addition to economical benefits, another advantage of the body and ring system is the ability to vary ring materials easily.

As mentioned previously, the precision of a rolling machine depends on its stiffness. Due to the fact that profile rolling machines have four rolls, the design space for each roll and its bearing, drive, and adjustment system is limited. Therefore, the stiffness of a four-roll profile rolling machine is less than that of a two-high rolling machine with the same roll diameter. The maximum degree of forming is also lower than on a two-high rolling machine. Whenever possible, two-high rolling machines should be used for pre-profiling and profile rolling machines should follow downstream in the production line to finish the shape.

Due to limited stiffness of older profile rolling machine designs, the *interlocked roll system* (see Fig. 15) was used to reach acceptable wire tolerances. This interlocked system uses precisely shaped rolls that touch each other and are preloaded with a force that is higher than the rolling force needed for the actual rolling process. As long as the rolling forces are below the pre-load force, the contact gaps between the rolls stay closed and the wire tolerances generally depend on the precision of the roll profiling process (usually grinding).
The interlocked roll system compensates for machine elasticity and is not sensitive to roll expansion caused by heat. Even old machines with worn-out roll bearings can reach acceptable results if precise ground and interlocked rolls are used.

The interlocked system has the following disadvantages:

- The wire dimensions cannot be changed by roll adjustment. Often many trials are needed to find the correct roll shape because the springback expansion of the wire and the deformation of the contact zone between the roll and wire affect the process.
- The contact between the rolls is critical with regard to abrasive and adhesive wear. The use of hardened tool steel as roll material is acceptable. However, today’s increased wire tensile strengths and demands on production speeds require different roll materials such as tungsten carbide. The direct contact between tungsten carbide rolls creates heavy wear and ultimately results in breakage. Therefore, the interlocked roll system is limited to applications in which the use of tool steel rolls is sufficient.

To overcome mechanical problems, actual profile rolling machine designs have been improved, especially with regard to stiffness (see Fig. 16). Tightest tolerances in the range of +/-0.003 mm at
production speeds of up to 800 m/min. can be realized today without interlocking the rolls. Nevertheless, very tight gaps are used because many shapes require sharp corners, and gaps between the rolls would result in finned wires. The most modern machines are equipped with a computer-controlled roll calibration and set-up system to achieve a balance between the need for minimum gap without the pre-loaded contact of the rolls.

Fig. 15. Interlocked roll system.

Fig. 16. Modern design of a standard profile rolling machine.
Universal Profile Rolling Machines. Basic profile rolling machines require a specific set of shaped rolls to produce the special shapes dictated by each wire profile.

A variation of the basic profile rolling machine was developed in the past for production of rectangular shapes, which accounts for the largest production volume of shaped wires. The design of this machine extends the basic design by the axial adjustment of each roll resulting in a universal rolling machine profile (see Fig. 17).

The combination of radial and axial roll adjustment provides a roll set-up that allows for the production of rectangular wires of different dimensions with one single set of rolls (see Fig. 18).

Even trapezoidal shapes of different sizes can be made in a certain range as long as the trapezoidal angle does not need to be changed.

To simplify set-up and operation, the axial adjustment of one roll is linked to the radial adjustment of the neighboring roll. When rectangle dimensions are changed, only the radial adjustments need to be moved.

Some universal profile rolling machines also provide a “Standard profile rolling machine” mode in which the linked operation of axial and radial adjustments are disconnected and the axial adjustment systems are fixed in a central position.

Due to limited axial bearing capacity it is not possible to close the gap between the rolls with pre-load forces in the linked universal mode. This means that an interlocked system, in order to increase wire accuracy as used in standard profile rolling machines, is not possible here. For this reason, the old and elastic designs of universal profile rolling machines cannot meet today’s tolerance requirements. This elasticity also complicated the use of tungsten carbide as roll material because it was almost impossible to prevent roll contact in the gap zones due to elastic roll deflection during operation.

The actual designs of driven and undriven machines in different configurations have improved stiffness to keep the adjusted gaps between the rolls constant (see Figs. 19 and 20). Another development is the computer-controlled roll adjustment and roll calibration, which decreases set-up times and guarantees an operator-independent setup. This is an immense improvement because the manual adjustment of the linkage of axes has proven to be the main source of error with regard to wear, breakage of rolls, and finned wires.
Fig. 17. Schematic sketch of the universal profile rolling machine.

Fig. 18. Change of dimensions with a universal profile rolling machine.
Special Rolling Machine Designs

Other machine designs have been developed to serve special applications, and these designs are mainly variations of the standard profile rolling machine. One example is the three-roll profile rolling machine, which is used for round wire production or ribbing of reinforcement steel wires (see Fig. 21).

Another example is the six-roll profile rolling machine for hexagonally shaped wires (see Fig. 22).

Components for Rolling Mills

Many other components are needed to create a complete rolling mill. This chapter provides only an overview of equipment necessary to complete the production line.

Payoffs

The payoff machinery marks the start of a rolling mill line. It presents the interface to the preliminary production units such as hot rolling or drawing lines. The function of the payoff is to accommodate the inlet wire in whatever way it is provided.

Fig. 19. State-of-the-art universal profile rolling machine with driven top and bottom roll and undriven side rolls.

Payoffs can be classified into two groups: static and dynamic designs, in which the wire bunch is either static or rotational during
line operation. One advantage of static payoffs is that they are generally easier to operate than the dynamic payoffs and they cost less.

Another advantage is that the static wire bunch allows the welding of single lots during line operation, which is not possible with dynamic payoffs. The grade of efficiency of lines equipped with static payoffs is higher compared with dynamic payoff lines.

When wire straightness is a main requisite, dynamic payoffs are preferred. The helix created in the wire during static take off leads to irregular and alternating curvature of the paid off wire and finally to straightness problems in the final wire.

Fig. 20. Modern design universal profile rolling machine with eight adjustment motors for computerized roll adjustment.
For both static and the dynamic payoff applications many different machine designs exist that have been adapted to the way the wire is packaged and handled. The main difference in packaging is whether the wire comes layer wound or as loose coils. Layer winding is advantageous because it allows for the application to and control of pulling forces on the wire without the risk of wire tangling due to coil contraction.
Some examples of dynamic payoffs are:

- Spool payoffs, in cantilever (see Fig. 23) or sleeve design for wire, that are layer wound on spools. For layer-wound, coreless coils these payoffs are equipped with expandable mandrels. This payoff type is available with or without a drive and in either case the package rotates.
- Dynamic horizontal coil payoff (see Fig. 24). This type is mostly used for wire rod with diameters greater than 12 mm, and it is the only type that can handle wires bigger than 20 mm. A drive and a simple straightener are usually integrated to simplify coil handling.
- Dynamic vertical coil payoffs (see Fig. 25). This type is designed for wires up to 20 mm diameter provided as loose wound coils or coils on carriers. Below speeds of 100 m/min, a drive is not required and a straightener is not integrated.

Examples of static payoffs include:

- Flyer arms for small wires up to 2 mm on spools or spooled as coreless coils (see Fig. 26). Flyer arms are not driven. They incorporate a brake to adjust wire tension. Sometimes a straightener is integrated.
Over-head coil payoffs (see Fig. 27) for wire coils up to 12 mm diameter provided coreless wound, on pallets, on carriers, or in barrels. The wire is pulled upward out of the package; it is pre-straightened; and tangles are removed on the way up by the weight of the wire.

Usually two coils are put underneath the deflection roll. The end of the wire coil that is in operation can be welded to the start of the next coil. This operation method allows for continuous production.

Static horizontal coil payoffs mainly used for hot rolled wire rod, coils up to 12 mm wire diameter. They are easy to load, because coil transport is usually made in the horizontal position and no tilting is required during loading.

The risk of wire tangling is higher in static horizontal payoffs compared to over-head coil payoffs because there is no equivalent to the gravity that pre-straightens the wire. Modern designs feature flyer arms or other mechanisms to keep the entire coil from being pulled from the payoff in the event of wire tangle. These models also allow loading and welding functions for continuous operation.

Fig. 24. Horizontal coil payoff.
Straighteners

Raw wires are usually paid off in a wound state necessitating a straightening process to receive straight wires after passing the mill’s rolling machines. Unlike wire processing machines, such as spring coiling or bending machines, the rolling process is not too sensitive to curved inlet wires. The rolling process itself improves the wire’s straightness provided that rolling is done with adequate wire guiding and tension.
Nevertheless suitable roller straighteners arranged in two planes (horizontal and vertical) with five (see Fig. 28) or seven rolls each should be used between the payoff and the first rolling machine.

Fig. 27. Vertical coil payoff.

Fig. 28. Five-roll horizontal straightener.
Especially when asymmetric shapes (e.g., trapezoidal, half-round or triangular form) are rolled, it may be difficult to control straightness just by means of guiding and tension. In these cases 9-, 11-, or 13-roller straighteners are used before winding the wire. This straightening operation requires extreme care because the wire is already finish rolled at this point of the mill and further roll contact can change the shape’s form and dimensions or scratch the wire’s surface. To reduce this risk, the straightening rolls are usually adapted to the wire shape by profiling the grooves on the rolls.

Straightening at this stage, compared to straightening the inlet wire, requires much more effort and is only done if other measures do not meet the straightness requirements.

**Cleaning Systems**

In rolling mills wire cleaning is typically applied to the inlet wire before rolling and to the finished wire before winding.

*Inlet Wire Cleaning.* Cleaning of the inlet wire is done for different reasons:

- The degree of forming ability increases when residual drawing lubricants are removed because the increased friction coefficient allows bigger reduction without slippage.
- Cleaned inlet wire will show smaller dimensional variations after rolling because the variations of the cleaned wire’s friction coefficient are smaller than those of a polluted wire, and these variations cause dimensional variations as they affect the degree of spread.
- The surface quality of the rolled wire is improved.
- The lifetime of the coolant in the rolling machine is extended because the lubricant does not have to absorb the impurities that are released during rolling.
- Surface impurities, such as scale, cause extensive machine and tool wear.

The cleaning method is selected with regard to the impurities that must be removed:

- Hot-rolled wire rod is covered with scale. Since batch descaling by pickling has become environmentally unpopular and because the final liming also is a contaminate that influences
the rolling process, the methods of inline descaling have become more important. Best results are reached by shot blasting (see Fig. 29), but this process requires a relatively high investment and maintenance. The method of cracking the scale by bending the wire with rolls and subsequent brushing is an alternative. The cleanliness after inline descaling depends on the line speed. Higher line speeds require more effort in descaling technology and the inline descaling unit may bottleneck the line with regard to speed.

- The drawing process for steel wires uses dry or wet lubricants that usually are not removed after drawing. Residual lubricants can be removed by washing (preferably with the heated and high pressured rolling process lubricant), brushing, or ultrasonic cleaning. As each of these methods has its pros and cons, the selection is made according to investment and maintenance costs, required line speed, and cleanliness.

![Fig. 29. Descaling by shot blasting.](image)

*Finished Wire Cleaning.* Cleaning of the finished wire is necessary to:

- keep the rolling machine lubricant inside the machine instead of carrying it out.
- meet the cleanliness requirements for finished wire.
Common cleaning methods include:

- Wiping the wire surface to remove rolling lubricant. The most effective material for wiping (e.g., sponge rubber, felt, leather, wood) is often found by a trial-and-error method, since no material is universally applicable.

As the wiper picks up the dirt, its cleaning performance degrades. Therefore, required maintenance is important.

Air wiping is one method to clean finished wire. It involves blowing off the lubricant used for rolling with compressed air applied with specially designed nozzles developed according to the wire’s shape. This method is almost maintenance free since there is no wear of the nozzle (see Fig. 30).

Air wiping is expensive due to the high production costs of compressed air. Therefore, it is usually used in combination with mechanical wipers. First the lubricant is wiped off and then residual film is blown off.

**Ultrasonic Cleaning.** This process achieves better results than wiping, blowing, or their combination, but it means another level of investment and maintenance since an ultrasonic cleaning unit is a complex system. The system comes with a sound transmitting fluid that picks up the removed dirt and, therefore, needs replacement or cleaning. Furthermore the required space for an ultrasonic cleaning
unit is considerable, at least when high production speeds are
demanded.

**Calibration Units**

Each wire that is produced by rolling requires an inlet wire with
a specific section area—usually a specific round wire. The degree of
spread, which determines the inlet wire dimension, is influenced by
a combination of parameters and the ideal inlet wire dimensions may
differ from one day to another.

Ferrous wires with low tensile strength provide influence in
spread by tension adjustment between rolling stands or by the mod-
ification of the rolling sequence. In contrast high tensile wires show
almost no reaction to these measures.

To adjust dimensions of the inlet wire to the actual demand of the
process and to minimize the inventory of inlet wires to be kept in
stock, an inline calibration of the inlet wires is advantageous. Since a
die calibration—at least for steel wires—requires a special wire prepa-
ration, the calibration by rolling is beneficial (see Fig. 31). Therefore,
a single drum capstan and an undriven rolling machine (typically a
simple cassette style with two pairs of rolls for round-oval-round
reduction) is the most suitable equipment for calibration.

**Guiding Systems**

Wire guiding is often underrated. At the positions where the wire
enters and exits the roll gap, guides help to:

- fill the caliber that is built by the shaped rolls in the
  intended way. Trapezoidal shapes, for example, will show
different corner radii because of lateral forces during rolling
  if no inlet guide is used and they will be curved because of
different elongation along the long and short sides of the
  shape if no outlet guide is used.
- force the incoming wire to enter the caliber slightly beside
  its center to create a trapezoidal shape with four identical
  radii. Outlet guides can obviate wire bending when exiting
  the caliber. Guide straightening can eliminate the need for
  straightening rolls.
- minimize dimensional variations because wire vibrations are
damped.
Guiding can be affected by shaped guide rolls, nozzles, or guide rails. Rolls are advantageous because of their smooth contact with the wire. However, due to the size of the guide rolls their distance to the roll gap is rather great and guiding performance is low.

Nozzles are ideal for round wires as their round bore is easy to make. In contrast manufacturing costs and their disability of adjustment inhibit the use of nozzles for shaped wire.

Due to the above reasons guide rails in many cases are the best solution with regard to effectiveness and cost. Usually two rails are applied across from each other. Each rail is adjustable. Either the complete rails are shaped to adapt the wire’s profile or the rails are equipped with shaped mouthpieces.

Depending on the application, guides are made of hardened steel, tungsten carbide, ceramic, or plastic.

**Synchronization Units**

Rolling mills incorporate numerous electrically driven units that are involved in transporting the wire, such as payoffs, rolling machines, capstans, and spoolers. Due to wire elongation during rolling or drawing the material’s speed increases when it passes the mill. The inlet wire is moving slower than the outlet wire.
Moreover the drives of payoffs and spoolers have to adapt to the actual coil diameters for unwinding and winding the wire with proper tension.

In a multi-stand rolling machine, usually the last driven rolling machine or the last capstan is the speed master for the line. The speed of the other driven machines—also referred to as slaves—is synchronized to this speed master by means of dancers or tension control units.

**Dancer Control.** Dancers (see Fig. 32) are able to accumulate a certain volume of wire by means of one or more moveable deflection rolls if the speed of the slave is too slow or too fast. The term “dancer” is used for these systems because of the motions of the moveable roll. By preloading the deflection rolls by weight, spring, or a pneumatic cylinder, the wire is always tied. Moreover the wire tension can be adjusted by changing the preload.

![Fig. 32. Dancer integrated in cooling basin.](image)

If the slave’s speed is too slow or too fast, this will increase or decrease the amount of wire stored in the dancer and the moveable dancer roll will indicate this asynchrony between the speed of the master and slave by leaving its neutral position. By means of a sensor, which forwards the position of the moveable roll to the electrical drive control, the speed difference is detected and compensated by the control system until the moveable roll has returned to its neutral position.
Due to the increased dynamics of today’s control systems these movements are almost invisible in state-of-the-art rolling machines.

**Tension Control.** A tension control system also uses a deflection roll. Unlike in a dancer it cannot move, but it incorporates a load cell instead. The load cell’s signal is proportional to the wire tension.

The main difference compared to dancer control systems is that tension control systems do not accumulate wire. Any speed asynchrony immediately changes wire tension. By adjusting the speed of the slave with regard to the load cell signal, tension is kept constant.

The operation of dancer-controlled lines is easier, since the dancer’s ability to accumulate wire reduces the risk of breakage or slippage due to excessive tension, especially during line set-up and wire threading. However the intense wire bending in dancers limits its use to wire thicknesses below 8 mm. Larger sizes require the use of tension control or torque control.

**Torque Control.** Unlike dancer or tension control units a torque control system is a speed control technique integrated into the electrical control system. The premise is to limit the torque of the slave motor to just below the torque needed to drive the rolls. The wire passes the slaves before it enters the master. Because the torque of the speed master is unlimited, the master pulls all slaves and the wire is always tensioned.

The difficulty with this system is adjusting to the slaves’ torque limitation. If torque is too low, the wire might break or slip. If torque is too high, wire loops will show up between rolling machines. Unlike dancer and tension control systems there are no feedback signals to indicate the wire tension or to enable an automatic adjustment. Each change of machine load, which is affected by roll adjustment, changes torque requirements and forces the operator to adjust the torque limitation.

The main advantage of torque control is that wire deflection is not needed, minimizing the distance between stands.

**Inline Measuring Systems and Automatic Gauge Control**

Up to line speeds of 40 m/min. skilled operators are able to check wire dimensions with a micrometer screw without reducing line speed. However, safety regulations do not allow this form of measurement because in most countries line operation at speeds above 15 m/min. requires closed machines that restrict the operator’s access to the wire.
It is possible to check wire dimensions when the line is stopped or in the creep speed range below 15 m/min. where safety covers may be opened. However, as mentioned before, wire dimensions at high speeds differ from those at low speed or standstill because of roll expansion due to heat, machine distortion due to heat, and speed dependency of wire spread.

To determine the actual dimensions at high speeds without the ability of measuring during operation, the line must be stopped and the finished coiled wire must be unwound to be able to check dimensions of a portion that was rolled at high speed. This method may be acceptable for a spot check to determine process accuracy, but it is unreasonable for modern quality management.

For the above mentioned reasons modern rolling mills incorporate inline measuring systems. The available units can be divided into two groups: contact and non-contact measuring systems.

Contact Measuring Systems. These systems contact the wire with sensors (or displacement transducers). Usually each measuring point uses two pairs of these sensors to touch the wire on opposite points. The wire dimension is calculated as an average of both signals to compensate for wire movement or vibration.

Standard contact measuring systems today use digital sensors (displacement transducers) and come with two pairs of sensors in two planes displaced by 90 degrees to measure, e.g., thickness and width of a flat wire or width and greatest thickness of a trapezoidal shape. Also special designs adapted to certain types of wire shapes are available.

Wire guides with rolls to prevent vibrations and wire twist (which would falsify the measured values) should be arranged in front of and behind the measuring unit. However, measurement errors due to wire twist is less critical in contact measurement systems as it is in non-contact systems.

Contact measurement units reach accuracies in the range of +/-0.001 mm.

Non-contact Measuring Systems. The most common type of a non-contact measuring system is the laser gauge, which is based on the shadow measuring system. Parallel laser light is emitted by a transmitter toward a receiver, and the wire is put between the transmitter and receiver. The size of the receiver’s shadow zone is determined, which corresponds to the size of the wire.
Just like contact measuring systems, laser gauges usually check two dimensions by integrating two transmitter-receiver units with 90 degree displacement in a collective housing.

Laser gauges are very sensitive against wire twist. Thickness measurement of a wide flat wire is critical because a slight wire twist will increase the shadow immensely. Width measurement of the same flat wire is much less critical. Therefore, sometimes for flat wire measurement combinations of a contact measurement system for thickness and a laser gauge for width are found because they are less expensive (see Fig. 33).

Since laser gauges do not contact the wire, they cannot distinguish between wire material and adherent residual coolant or dirt, thus making wire cleaning before measuring critical.

Wire gauges are very precise. They reach accuracy in a range below +/-0.001 mm.

A different approach to non-contact shape measuring is the light section method, which uses lasers and cameras to determine wire dimensions like thickness and width. These criteria are displayed on a computer monitor where they can be compared to maximum and minimum shape tolerances.

The accuracy of the systems currently available is in a range of +/- 0.005 mm, which is not acceptable for many of today’s applications.

Once the actual dimensions of the wire are available, these values can be processed in the machine’s control system called
Automatic Gauge Control (AGC). Reports can be printed; statistical evaluations can be provided; and the actual dimensions can be used to automatically adjust the machine to the nominal wire dimensions.

Then, when the actual and the nominal dimensions are subtracted, the difference is fed into the roll adjustment of the roll that creates the accordant dimension. For example, in a standard flattening line the thickness control adjusts the final two-high stand and the width control affects the last edger.

State-of-the-art rolling mills do not restrict the AGC to the last rolling machines for each axis. They allow a free combination of line roll adjustments and measuring points. For example, all roll adjustments of two-high units in a flattening mill could be controlled by the thickness—AGC. This results in a smoother behavior of the entire line since heat compensation is dispersed to all two-highs units.

**Pulling Devices**

Undriven rolling machines and drawing dies require a means to drive the wire. In wire rolling machines the following pulling devices are used for this task.

*Caterpillar Pull-offs.* Two driven belts made of steel cord reinforced rubber are pressed toward each other and form a common straight channel into which wire is fed. The advantage of a caterpillar pull-off is its friendly operation to the wire surface. Nevertheless, due to the frictional contact between belts and wire the maximum traction force is limited. Caterpillars are often found in electric cable machinery and only seldom in wire processing machines.

*Single-Drum Capstans.* Capstans equipped with a single conical drum are typically used in single- or multistand drawing lines for round wire. In rolling machines single drum capstans are used for inline round wire calibration with drawing dies or friction-driven rolling machines. The wire is wrapped around the drum between three and eight times.

The drum is conical and it is limited by a flange at the greater diameter of the cone. The incoming wire squeezes in the gap between the flange and first winding, and this forces the windings to slide on the drum away from the flange. The drum’s conical form allows the wire to release tension with each turn. If the cone angle is too great, the capstan’s pulling ability is limited due to fast tension release and related slip. Cone angles that are too small inhibit the
axial wire sliding because of tension-related high-contact forces. The wire will build up at the flange.

Water-cooled drums are sometimes used to cool the wire. In this case capstan designs with vertical axes are preferred. Horizontal axes are used sometimes also.

The major disadvantage of single drum capstans is the wire surface damage caused by the sliding movement between wire, drum, and flange; the wire-to-wire contact creates scratches.

**Double-Drum Capstans.** To avoid wire surface defects the double drum capstan was introduced to the wire processing industry (see Fig. 34). The axial displacement winding by winding is realized by slightly tilting one of the drums, which eliminates surface defects that would have been caused by flange and inter-wire contact. The drums are cylindrically shaped or are minimally conical.

![Double-drum capstan.](image)

Because of the mechanical features of the double-drum design it is often used for shaped wires that would be damaged on conical drums. For final, favorable skin passes a combination of undriven profile rolling machines and a double-drum capstan is used. Unlike driven rolling machines there is no risk of slippage when undriven rolling machines are used for skin passes. Moreover the capstan acts as isolation for vibrations between the rolling and the coiling section of a mill. Any vibration created by the coiling process (e.g., layer winding) cannot pass through to the rolling machines. As a result, the dimensional accuracy of the rolling process is enhanced.
Actual double-drum capstan designs come with two driven rolls, a motorized tilting system, tungsten carbide drum coatings, and water-cooled drums.

**Take-ups**

The take-up unit represents the end of a rolling machine. Take-ups are the interface to the shipment packaging or to downstream processing machines, functioning to prepare the wire product in whatever way it is required.

Take-ups can be classified in two basic groups: static and dynamic designs that bunch the wire statically or through rotation during line operation. One advantage of static take-ups is that in most cases they are simpler than dynamic take-ups, which makes investment and operation costs lower.

In lines where wire straightness is a main issue, dynamic take-ups are preferred. The helix created in the wire by static take-ups leads to straightness problems in downstream wire processing.

Unlike round wiredrawing machines, shaped wire rolling machines very seldom use static take-ups. One example is the *dead block coiler*, which can be used for small wire dimensions. The wire is coiled onto carriers or into barrels.

Many dynamic take-up designs exist that can be adapted to the required packaging. The main difference in packaging is whether the wire is layer-wound or if loose coils are produced. Layer-winding is advantageous because it offers easier unwinding in the subsequent wire processing machines and surface defects are minimized.

Examples of dynamic take-ups include the following.

**Oscillation-spoolers.** Oscillation-spoolers exist in cantilever or sleeve design (see Fig. 35) for wire that is layer-wound on spools. To create layer-wound coreless coils these spoolers are equipped with expandable mandrels.

To lay the wire precisely layer by layer, it is advantageous to traverse the spool so that the wire maintains its straight direction out of the rolling machine. Although more expensive, this system compared with the alternative—traversing wire and non-mobile spool—results in fewer injuries and better wire straightness after uncoiling.

Today the traversing systems are usually computer-controlled and provide some special features to generate faultless spools.

**Dynamic Horizontal Coilers.** This type of coiler is used mostly for large shaped rod with dimensions greater than 100 mm² and it is the
only type that can handle wires greater than 400 mm$^2$. As the wire is coreless wound, plastic bending is required, and this is created by a set of adjustable bending rolls. Some types come with oscillating bending rolls to create more compact coils (see Fig. 36).

Dynamic Vertical Coilers. The basic concept is identical to the dynamic horizontal coiler. The design is simpler and the concept allows for the use of two carriers to minimize downtime. Few take-ups of this design are found as most wire shapes do not allow the bending of the rolled wire around its vertical axis.

![Horizontal spooler in sleeve design.](image)

Due to the weight of the wire windings that hang on the bending rolls this coiler type tends to create wire torsion especially when large sections are processed. Therefore the application of this type of take-up is limited to sections below 200 mm$^2$.

Shears and Saws

Many wire products are based on cut-to-length bars. Instead of coiling the wire after rolling and subsequently de-coiling, straightening and cutting, it is alternatively possible to integrate the cut-to-length process in the rolling machine.

Cutting refers to the different ways of dividing the wire into sections. In practice different methods such as shearing and sawing are commonly used, and laser and jet-cutting are also possible.

As the cutting and subsequent bar handling processes are not continuous processes during rolling, they usually limit the line speed.
Rolling machines with integrated cutting equipment are primarily found where large wire sections are processed, because their line speeds usually are lower, and straightening and cutting on separate lines is more intricate for large sections than for small.

Cutting-to-length processes differ in systems that stop the wire for cutting (static systems) and others that accelerate the cutting system to wire speed before cutting (dynamic or also called flying systems).

Static systems require an accumulator in front to collect the wire during the cutting process and a clamping system to stop the wire movement during cutting. Because the accumulator grows in size with the wire section, static cutting systems are limited to wire sections below 100 mm². The cutting is done with hydraulic shears, cutoff grinders, or bandsaws.

For larger sections the cutting system is mounted on a driven platform that accelerates to wire speed, cuts, and moves back to its starting position. These flying shears or flying saws (see Fig. 37) are equipped with powerful drives. The cycle time for acceleration, cutting, deceleration, and return movement limits the line speed to a maximum 100 m/min. For bar lengths below 2 m the maximum line speeds are even slower.
Lubricating and Cooling System

In rolling machines the coolant serves two purposes: wear protection and cooling.

**Wear Protection.** With regard to wear reduction, the function of the coolant is to separate metallic surfaces by building a lubricating film between them. This film has to withstand the rolling force and high local temperatures.

The quality of the lubrication film also affects the quality (degree of roughness) of the wire surface.

**Cooling.** Without cooling, especially in multi-stand lines, the wire temperature would rise stand by stand. The result would be a loss of quality with regard to dimensional accuracy, because:

- As the friction coefficient between wire and roll changes wire spread differs.
- As the yield strength of the wire decreases, wire spread differs. This leads to lower separating forces followed by dimensional variations because of the elasticity of the rolling machine.

Insufficient cooling can create other problems when wires are layer-wound on spools. The wound package shrinks during cooling and this damages either the spools or the wire.
Two types of coolants are used in cold rolling processes: pure oils and emulsions made of soluble oils and water.

The higher the lubricant viscosity is, the smoother the wire surface will be. Therefore, thick oils are preferred over emulsions when surface quality is the main concern. On the other hand, the cooling efficiency of emulsion is approximately twice as high compared to pure oils.

To minimize wear and to cool the rolls, the coolant is sprayed into the contact zones between wires and rolls. For efficient wire cooling between stands, modern rolling machines come with cooling zones such as flooded dancer control basins (see Fig. 32).

The lubricant is contained in a tank for each rolling machine or a central tank to serve multiple lines. The tank is connected with piping, and the flow pump and return pump control the coolant cycle (see Fig. 38).

As the energy needed for the rolling process heats up the wire and the wire adds heat to the coolant, the temperature in the tank rises during machine operation. To keep the coolant temperature within an ideal range, the tank is usually equipped with a re-cooling system such as a water-cooled heat exchanger.

For high precision wire rolling, even-heating systems are used to maintain proper coolant temperature during standstill times such as machine setup or weekends.

Another important lubricant issue is its cleaning. Sedimentation is the most effective cleaning process, but because it is extremely slow, it is not applicable. Therefore, filtration is needed. Depending on purity requirements, the filtration either is handled in the mainstream of the return pump or in a separate cycle that houses its own pump.

The purity of the coolant is important with regard to the lifetime of the coolant (especially when emulsion is used), machine cleanliness, and wire surface quality.

**Electric Control**

In the beginning of the industrialization era in Europe, man built the first machines to produce round wires. Instead of pulling the wires manually through iron dies, the first capstans were used to draw small batches of wire in a single-pass process. These capstans were usually driven by steam engines and transmission belts. The first driven rolling machines—simple two-high designs with manual adjustment—were driven by the same power source.
When the electric motor was developed around 1870, it displaced the steam engines. The single-stand rolling machine design was not replaced, however, until around 1950 when speed control of D.C. motors by converters was introduced into the machine-making industry. From then on it was possible to build multistand machines with independent speed-controlled drives that enabled wire elongation during rolling and spooling with constant tension independent of the actual spool diameter.

Control signals were originally analog. For example, a motor revolution between 0 and 1500 rpm was controlled by a speed-proportional signal of 0 to 10 V set by a potentiometer or by the position of a dancer arm. The motor’s tachometer fed back an analog voltage that was proportional to the actual speed of the motor.

In addition to speed and tension control, these analog drives were also used for the first automatic gauge controls. The electric control automated roll adjustment and increased dimensional accuracy.

In the late 1980s the first programmable logic controls (PLCs) were introduced into rolling machines (see Fig. 39). Instead of wiring between sensors (e.g., push buttons, limit switches, etc.) and actors (e.g., motors, valves, etc.) the sensors and actors are connected to the input and output of the PLC hardware. The linkage between input and output is made by a software program. Machine functionality is much more flexible and versatile. Software modifications are made in minutes. If necessary the service is done via remote access by modem or Internet.

In the mid 1990s the electronic speed and torque control of A.C. motors was improved. From then on the A.C.-technique was pre-
ferred because of the low maintenance requirements of the A.C. motor and its ability to operate even in dirty or wet environments.

![Movable operator panel.](image)

Today A.C. motors represent the industrial standard. Servo- or step motors are used only in situations that demand the highest speed, accuracy, or dynamics. In high-dynamic applications such as high-speed oscillating spoolers even linear drives are found.

The control is generally done by a PLC. Instead of one PLC in the machine’s central cabinet, decentralized PLCs are used in cabinets of line components such as payoffs, rolling machines, and spoolers. The PLCs are connected via a bus system. The cabling is simplified and due to short cable lengths connectivity problems are reduced.

Machine operation is done on PC-like touch panels instead of using push buttons. Machine setups are stored in and loaded from recipes. The control is connected to the Internet to provide worldwide remote service.

The precision of today’s electric controls has increased the accuracy of the rolled wires. At least 50% of a mill’s quality is reached by software engineering.
Some Typical Rolling Mills for Ferrous Wires

The previously described components are used to design complete rolling mills. Typical examples include:

**Reduction Rolling Mills**

Unlike the drawing process the rolling process does not require any wire preparation such as coating to improve the efficiency of the lubricant. Therefore, the surface quality of the final wire after rolling is better than after drawing. For this reason rolling competes with drawing, and rolling machines are becoming more and more popular for round wire reduction (see Fig. 40).

**Flattening Mills**

In flattening mills the wire is rolled alternately vertically with two-high rolling machines and horizontally with edgers (see Figs. 41 and 42). When dimensions are changed, only the profiled edger rolls need to be changed. Depending on wire dimensions line speeds between 80 and 800 m/min. and dimensional accuracies between +/- 0.003 mm and +/- 0.020 mm are reached.

**Shaping Mills**

In shaping mills the wire is rolled with profile rolling machines (see Figs. 43 and 44). Very often a two-high machine is found as the first stand to create spread. Depending on wire dimensions line speeds between 40 and 500 m/min. and dimensional accuracies between +/- 0.003 mm and +/- 0.020 mm are reached.

![Diagram](image-url)  
Fig. 40. Reduction rolling mill with round→hexagon→round system.
CHAPTER 28 — ROLLING FLAT AND SHAPED WIRE

Fig. 41. Two-stand flattening mill.

Fig. 42. High-speed flattening mill.

Fig. 43. Two-stand shaping mill.
Fig. 44. Modern five-stand shaping mill with housing.