HOT ROLLING PRACTICE – An Attempted Recollection

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Rolling is a metal forming process in which metal stock is passed through a pair of rolls. There are two types of rolling process - flat and profile rolling. In flat rolling the final shape of the product is either classed as sheet, also called "strip" (thickness less than 3 mm,) or plate (thickness more than 3 mm). In profile rolling, the final product is either a round rod or other cross sections shaped products such as structural sections (beam, channel, joist, rails, etc). The initial breakdown of ingots into blooms and billets is done by hot-rolling. The process involves plastically deforming a metal work piece by passing it between rolls. Rolling is the most widely used method of forming / shaping metals, which provides high production, higher productivity and close control of final product than other forming processes. This is particularly important in the manufacture of steel for use in construction and other industries.

Hot Rolling Technology

Rolling is classified according to the temperature of work piece rolled. If the temperature of the metal is above its recrystallization temperature, then the process is termed as hot rolling. For hot working processes, large deformation can be successively repeated, as the metal remains soft and ductile. The metal stock is subjected to high compressive stresses as a result of the friction between the rolls and the metal surface. Rolling involves passing the material between two rolls revolving more or less at the same peripheral speed but in opposite directions, i.e., clockwise and counterclockwise. The distance between them is spaced, which is somewhat less than the height of the metal stock entering them. These rolls can either be flat or grooved (contoured) for the hot rolling of rods or shapes. Under these conditions, the rolls grip the piece of metal and deliver it, reduced in cross-sectional area and therefore, increased in length.

- The initial hot-working operation for most steel products is done on the primary roughing mill (blooming, slabbing or cogging mills).
- These mills are normally two-high reversing mills with 0.6 -1.4 metres diameter rolls (designated by size).
- The objective is to breakdown the cast ingot into blooms or slabs for subsequent finishing into bars, plate or a number of rolled sections.
- The blooms/slabs are heated initially at 1100^0 C -1300^0 C. In hot-rolling of steel, the temperature in the ultimate finishing stand varies from 850^0 C – 900^0 C, and is always above the upper critical temperature of steel.
- Steel is squeezed between rolls until the final thickness and shapes are achieved. To achieve this, rolls exert forces of tens of millions of Newton - equivalent to a weight of thousands of tonnes. The rolls run on massive neck bearings mounted in housings of enormous strength and driven by powerful electric motors. These are known as mill stands. The layout of a rolling mill varies, from a simple single stand mill to several stands positioned either side by side or in a line.

  A mechanism, commonly called a roller table, directs the work piece to the rolls, and another roller table for handling the pieces emerging out of the roll. The table in front of the rolls forces the steel against the rolls which grip and pull the steel between them. Steel is, thus, reduced to a thickness equal to the distance between the rolls, and if the rolls are grooved it is shaped according to the groove design.

Hot rolling permits large deformations of the metal to be achieved with a small number of rolling cycles.

Heating of Cold Stock

One of the prequisites of the hot rolling practice is heating the input bloom/billet/slab from the room temperature to the rollable temperature. At that higher temperature the steel is transformed in to a single austenite phase from the dual phases of perlite and cementite at room temperature. Such phase change temperature for 0.68 % carbon steel is 738^0 C. At lower or higher carbon percentage, this phase change temperature increases and therefore, the temperature to which the steel is heated for hot rolling is increased accordingly. However, in practice steel is actually heated to a temperature of about 50^0 C to 100^0 C above the phase change temperature. This increase in temperature is because steel besides having varying percentage of carbon and iron also contain other alloying elements which affect the phase changing temperature.

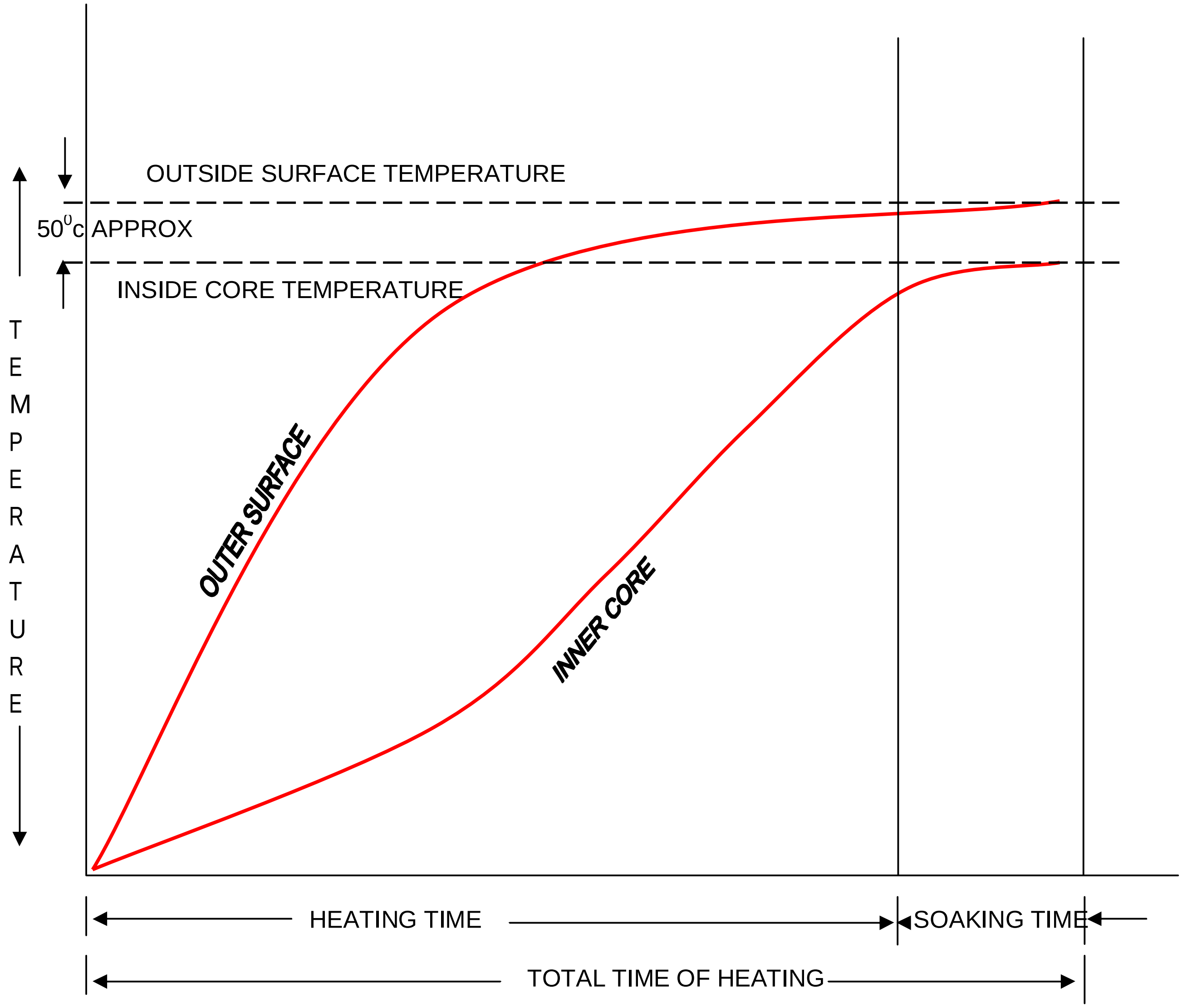
Hot rolling takes place in a number of steps and drafting / reduction is given in every stage. The ultimate draft is at a temperature above the recrystalisation or phase change temperature. Accordingly the cold stock is heated to a much higher temperature than the recrystalisation temperature. Therefore, the ultimate temperature to which the work piece depends on the amount of total draft, the number of steps where the drafting is provided and the composition of the steel stock. Blooms are heated to the rollable temperature in a reheating furnace. This is the starting point of the hot rolling mill practice.

Reheating Furnace

- Cold stocks are heated to make them soft and thus suitable for rolling.
- Furnace has three parts**:** walls, roof and hearth. Furnace is lined with several layers of refractory bricks. It is insulated by glass wool. The initial heating zone of the furnace has temperature of about 1000^0 C. This zone is lined with low alumina refractory bricks. Soaking zone has temperature in excess of 1200^0 C. High Alumina refractory bricks are suitable for this zone.
- Reheating is a continuous process where the cold stock is charged at the cold rear end of the furnace and heated. The hot blooms (in the rollable temperature) come out from the front, i.e., the discharged end of the reheating furnace and then proceed in the direction of rolling. Heat energy from the hot burner flames and flue gases is transferred to the cold input steel during their travel across, i.e., from the rear to the discharge end of the furnace. This exchange of heat energy takes place by means of conduction, convection and radiation by/from the hot flames, hot flue gases and the hot furnace walls. The rollable temperature of the hot blooms/slabs ranges between 1150^0 C-1200° C. Thus the temperature inside the furnace is still higher.
- There are many types of reheating furnaces with various designs. The workings of these furnaces are also unique in nature. Heating takes place by burning of fuel oil or gas inside the furnace with the help of combustion air supplied through an air blower. The air is the sole supplier of oxygen for the exothermic heat of reaction resulting from the oxidation of the fuel. This heat of reaction is the source of heat input in the furnace.

- Reheating for achieving the rollable temperature depends on the quantum of fuel (fuel oil /gas) burnt which in turn is dictated by the demands of the current rolling scenario. The quality of reheating depends on the criteria mentioned below:
    - ❖ The furnace throughput, i.e., the capacity of the furnace.
    - ❖ The asking / required rate depends on the current prevailing condition of rolling i.e., the expected present rolling rate.
    - ❖ The time duration of travel of the cold stock from charging end to the discharging end.
    - ❖ The dimension of the input stock being heated and the steel composition.
- Fuel burners are situated in the hearth area, i.e., soaking zone and the discharging end of the reheating furnace.
- The hot flames emerging out of the fuel burners glide smoothly over the charged stock and transfer their heat energy by conduction and convection of heat from the roof and the walls. The flue gas is drawn towards the rear (charging) end of the reheating furnace and finally escapes to the atmosphere through flue passage and chimney via the recuperator.
- The efficiency of this heat transfer depends on the lengths of the hot flames and the time duration the hot flue gas interacts with the cold stock.
- ▪ The conductivity of heat takes time and is strongly related to the composition of the material.
- ▪ The coefficient of heat conductivity is similar for many steel grades but is much lower in stainless steels.
- The lengths of the hot flames are controlled by the amount of fuel input and the corresponding combustion air (oxygen) blown in.
- The valves in the flue passage also play a major role in controlling the lengths of the flames and the time duration of the hot flue gliding over the stock. The amount of draft (suction) inside the furnace is maintained by controlling these valves. Opening the valves in the flue passage increases the draft which in turn lengthens the flame but shortens the duration the flue resides in the furnace for heat transfer. However, lower draft prolongs the duration of stay of the hot flue gas inside the furnace but reduces the flame length.
- By judicious controlling of the valves the heat input and the efficiency of heat transfer is controlled to significantly.
- The refractory lined walls of the reheating furnace get heated by the hot flames. These hot refractory brick walls prevent heat transfer, i.e., preserve of heat of the hot stock by preventing the dissipation of heat from the hot stock to the walls.
- Heating of the cold stock commences at the charging end of the furnace. The outer surface of the steel stock comes in direct contact with hot flue and so its temperature rises. As the stock travels forward towards the discharging end, it comes in contact with still hotter flue possessing higher heat content. The surface temperature of the stock further rises rapidly.
- Heat is transferred from the outside surface to the core of the stock by conduction which is a slow and time consuming process. During this period of heating, therefore, maximum temperature difference between the outside surface and the core exists.
- As the steel travels towards the discharging end it comes in contact with flue having highest temperature. While the temperature of the outside surface of the stock increases progressively, the temperature difference between the outside surface and the inner core also builds up considerably. Up to this stage, it is known as heating.

Graphical Presentation of the Heating Process

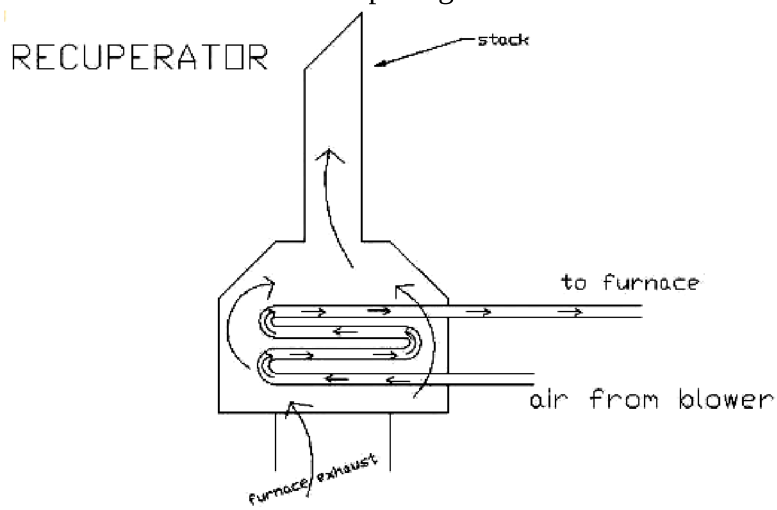


- The next/ultimate stage of the heating process is known as soaking, when the temperature difference between the outside surface and the inner core is gradually brought to a minimum. However, the temperature difference between the core and the surface is never made zero. The minimum temperature difference, as observed in practice remains roughly 50^0 C.
- If the air (oxygen) supplied is less than the minimum amount required for complete combustion of the fuel input, then some unburnt fuel is left behind. This is easily detected from the black smoke (unburnt fuel) emerging from the chimney top. A lot of precious fuel is thus lost to the atmosphere. This brings down the heating efficiency of the furnace and the cost of operation increases.
- Surplus cold air (oxygen) means more available oxygen. This excess amount of oxygen, besides being adequate for complete combustion of the input fuel, some balance amount is readily on hand for oxidation of the hot steel input to form scales on the surface. Oxidation reduces the metal output and consequently the yield percentage. The cost of production is thus adversely affected.
- Then the excess cold air blowing across the furnace carries away a lot of sensible heat energy from inside the furnace, resulting in the furnace running cold and thus lowering the heating efficiency.

- The hot flue escaping from the furnace by being sucked/drawn out through the chimney contains valuable sensible physical heat which unless tapped is a shear waste of heat energy to the atmosphere.
- If this otherwise lost heat is recovered and utilized in the furnace, the heat efficiency of the furnace is improved to a significant extent.

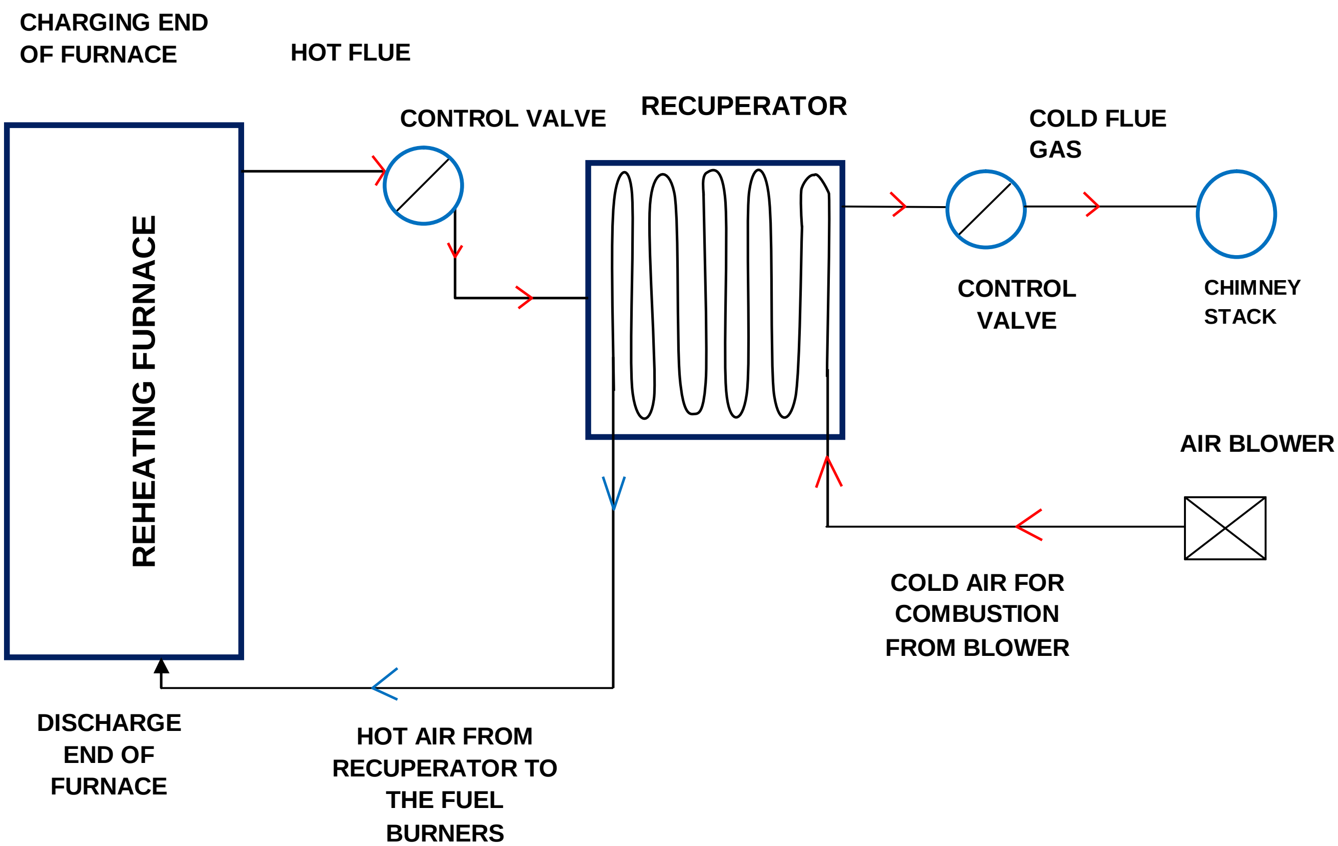
Recuperator - Its worth

- A recuperator is placed in the flue passage with two valves - one flanked by the recuperator and the furnace and the other in between the recuperator and the chimney.
- Cold air from the air blower, required for combustion of the fuel is passed through a pipe work placed inside the recuperator box, at right angles to the passage of the hot flue gas. The air pipe passing through the recuperator box is not a straight one. It is smoothly bent at 180^0 (with small radius curve) many folds inside the recuperator box. This increases the surface area and thereby the duration of contact between the hot flue and the cold air for efficient heat transfers. The pipe end having cold air enters the recuperator box from the rear end of the box and the pipe end with hot air emerges out from the front end of the box in the flue passage.



- Recuperator recovers the valuable physical heat contained in the hot flue and transfers same to the cold air (from the air blower), which is supplied to the furnace for combustion of the fuel.
- The total heat input to the furnace is the heat of the oxidation reaction between oxygen of the air and the fuel (gas/fuel oil) in addition to the physical heat recovered from the flue gas with the help of the recuperator.
- Therefore, this supplementary quantity of heat is actually made available without increasing the fuel input. The heat efficiency of the reheating furnace is thus greatly improved.
- By opening and closing the valves (dampers), the temperature inside the recuperator is controlled, i.e., to cool down or increase the temperature. If the temperature within the recuperator comes down then by closing the valve provided after the recuperator, the suction action in the flue passage is reduced. This increases the duration of stay of the hot flue inside the box. The temperature inside the recuperator is thus increased.

Presentation of Heat Transfer & Flow of cold Air & Hot flue



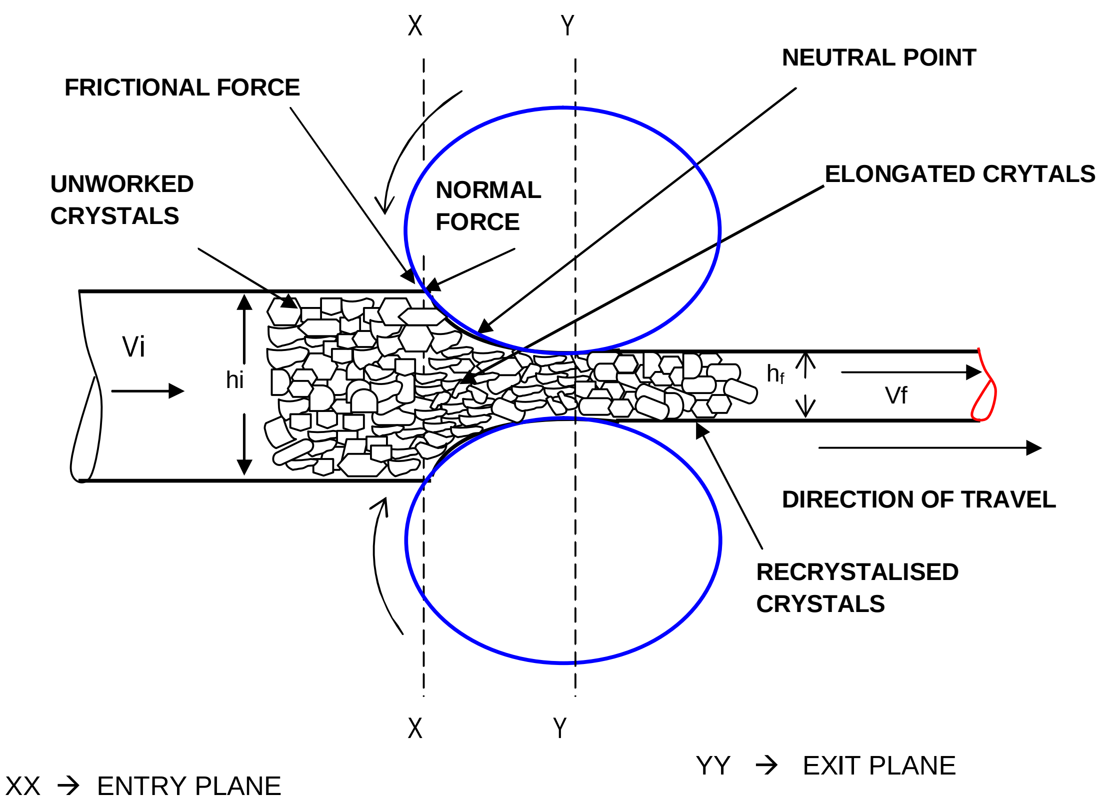
- On the contrary, if the temperature inside the recuperator goes up then by opening the valve after the recuperator, the suction action in the flue passage is increased. This decreases the duration of stay of the hot flue inside the box. The temperature inside the recuperator is thus decreased.
- The temperature inside the recuperator is never allowed to rise abnormally high as leakages develop as a result of the melting of the recuperator pipes. Leakages cause cold air to infiltrate into flue passage leading to lesser air available for combustion. Moreover, due to air infiltration suction in the flue passage is decreased with all its adverse consequences.
- The heat recovery ratios of recuperators compared to regenerative are low. In spite of recent improvements recuperators recover 70% - 80% of the waste heat and air is pre-heated up to 850^0 C - 900^0 C.

Recrystallization

- The distinction between hot and cold rolling depends on the processing temperature with respect to the recrystallization temperature of material.
- Rolling is classified according to the temperature of the metal rolled. If the temperature of the metal stock is above its recrystallization temperature then the process is termed as hot rolling, whereas if the temperature of stock is below its recrystallization temperature the process is known as cold rolling.

- Hot rolling is conducted by raising the temperature of the steel metal stock to its upper critical temperature to its austenitic phase, i.e., above the recrystallisation temperature. Then controlled load is applied which forms the material to the desired profile and specification.
- While the material is rolled, its temperature is monitored to make sure it remains above the recrystallization temperature. To maintain a safety factor, the finishing temperature is usually 50^0 C to 100° C above the recrystallization temperature. If the temperature does drop below this critical level, then it is not termed as hot rolling
- The austenite grains get deformed / elongated in the rolling direction. However, these elongated grains start recrystallising as soon as these come out from the deformation zone.

Hot Rolling & Recrystallisation



- The unidirectional austenite grains dissolve as soon as the temperature drops below the upper critical temperature. These are entirely replaced by a new set of grains, to nucleate / recrystallize and grow into ferrite-perlite structure. The recrystallized ferrite-perlite grains maintain equiaxed microstructure and prevent the metal property from becoming unidirectional and work hardened.
- It is usually accompanied by a reduction in the strength and hardness of a material and a simultaneous increase in the ductility.
- Recrystallization may occur during or after deformation (during cooling or subsequent heat treatment).

- The rate of recrystallization is heavily influenced by the amount of deformation applied. Heavily deformed materials recrystallize more rapidly than those deformed to a lesser extent. Indeed, below a certain percentage deformation recrystallization may never occur.
- Deformation at higher temperatures allows concurrent recovery. Materials recrystallize more slowly than those deformed at room temperature e.g. contrast hot and cold rolling
- The volume fraction of recrystallized grains increases with temperature for a given time.
- The most important industrial uses are the softening of metals previously hardened by cold work, which have lost their ductility, and the control of the grain structure in the final product.

Scale Formation & Its Effect

- The thickness / formation of scale is influenced by the temperature of stock being heated, the composition of the steel input, the furnace atmosphere (whether excess air or not), i.e., whether excess oxygen is available or not and the time of residence of the stock in the furnace. More time spent inside the furnace at a high temperature and oxidising atmosphere leads to thicker scales and thus more metal loss. It is observed in practice that maximum scale formation in steel take place at about 800^0 C.
- Formation of scale means loss of valuable steel metal. Generally, it is around 1% of the input weight. To produce this amount of steel metal, energy has been used in several steps: ore excavation and refinement, reduction, conversion, casting, and reheating. Reduction of scale losses is equivalent to a reduction of the total energy used to produce a certain quantity of steel.
- Improved control of the furnace atmosphere enables a lower and more stable oxygen content inside the furnace and hence reduction of metal loss through scale formation. However, most metal experience some surface oxidation resulting in material loss and poor final surface finish. A quality improvement of the reheating process due to automatic furnace control indirectly contributes to the energy efficiency and therefore, is accounted for in the same manner as direct fuel savings.
- However, a very thin scale is purposely formed on the outer surface of the stock to prevent dissipation heat from the hot steel.
    - Scale forms an insulating material cover resulting in very low heat conductivity.
    - After preheating steel slabs or blooms the rough material is descaled, but growth of secondary scale, a function of time starts immediately.
    - High temperature scale is very hard and the main cause of wear in work rolls. Low temperature scale is much softer. Rolled-in scale devalues the rolled products.
    - Descaling of secondary iron oxides is always highly recommended.

Metal Burning

- Another undesirable feature influencing metal loss to a great extent is burning of metal.
- This is caused by excessive heating resulting in burning / melting of the input stock, which leads to metal loss.
- This happens largely when the output is low or the rolling is not stable and steady but the corresponding fuel and air input remains unaltered and not changed duly. Loss of metal due to metal burning causes lower yield.
- The input steel on occasions is degraded because of excessive oxidation of carbon and other alloying elements in steel. This happens when the normal residence of the stock at an elevated temperature inside the reheating furnace is extended because of some reason or other.

- All such factors are taken into consideration when the furnace efficiency is calculated.
- Thus the quality of the reheating is important both from the energy input / transfer point of view and loss of metal due to oxidation / burning of metal (slag formation).

Typical Rolling Mills & Arrangement of Rolls

- A set of rolls mounted in a pair of housings constitutes a 'stand'. Stands are combined in various ways to produce different types of mill layout for special functions.
- Mills are classified according to the distance between centers, i.e., the pitch circle diameter of the pinions. The size is determined by the mean roll diameter. The difference in starting size and scrap size leads to the complication. However, it is often used on primary mills and in mills with no pinions but a separate drive to each roll.
- The stock moves at different velocities at each stage in the mill. The speed (RPM) of each set of rolls is synchronized so that the input speed of each stand is equal to the output speed of preceding stand.
- The production routes for long and flat products differ noticeably; therefore, the material flows of the rolling sections differ to some extent.
- Prior to continuous casting technology, ingots were rolled to approximately 200 millimeters thick in a slab or bloom mill. Blooms have a nominal square cross section, whereas slabs are rectangular in cross section.
- Slabs are the feed material for hot strip mills or plate mills and blooms are rolled to billets in a billet mill or large sections in a structural mill.
- The output from a strip mill is coiled and, subsequently, used as the feed for a cold rolling mill or used directly by fabricators. Billets, for re-rolling, are subsequently rolled in either a merchant, bar or rod mill
- Merchant or bar mills produce a variety of shaped products such as angles, channels, beams, rounds (long or coiled) and hexagons. Rounds less than 16 millimeters in diameter are more efficiently rolled from billet in a rod mill
- For the hot rolling of flat products the mills are considered to comprise cogging (usually 2-high stands) and intermediate (usually 4-high stands) trains and the finishing train (4-high stands) as well as crop shears for strip production and one or two reversing 4-high stands and shears for plate production.
- For the production of long products the mills usually consist of a series of reversible 2- or 3-high stands, that make the blooms pass gradually through the different grooves shaping its cross-section until the product is finished.

  Two-High Mill, Pullover : A stand (set of rolls) having two horizontal rolls one above the other is called a two-high stand. The stock is returned to the entrance for further reduction. This consists of two rolls, which may rotate only in one direction (non-reversing) or in two directions (reversing).

  Two-High Mill, Reversing : The work is passed back and forth through the rolls by reversing their direction of rotation. Two high stands is either reversing mills in which the steel passes back and forth between the same rolls or continuous mills in which the steel passes through several stands in tandem.

  Three High Mill : In three - high mills, three rolls are arranged vertically. Steel passes forward between the middle roll and bottom roll and backward between the middle and top rolls. This consist of upper, middle and lower rolls driven by electric motors and allows a series of reductions without the need to change the rotational direction of the rolls, i.e., directions of rotation of the rolls in three-high mills are not reversed.

Four-High Mill : Small-diameter rolls (less strength & rigidity) are supported by larger-diameter backup rolls. Using small rolls reduces power consumption but increases the roll deflection. In this configuration, two small rolls, called working rolls, are used to reduce the power and another two, called backing rolls, are used to provide support to the working rolls. Two backup rolls, generally much larger than the operating rolls, is placed against the two operating rolls to prevent their distortion. These are called four-high stands. Four-high stands is either reversing mills in which the steel passes back and forth between the same rolls or continuous mills in which the steel passes through several stands in tandem.

Cluster Mill Or Sendzimir Mill : Each of the work rolls is supported by two backing rolls. Another configuration that allows smaller working rolls to be used.

Tandem Rolling Mill : This is continuous rolling with series of rolling stands.

- In continuous rolling process, the long axis of the bar is brought between the rolls and is rolled in to a shape with equal axes. This shape is further rolled into a different shape with different axes, and so on. The reduction must be applied after a 90^0 rotation of the bar at each stand.
- Continuous bar mill consists of a number of independent stands; each has its own motor and whose rotational speed can be freely altered. The bar can be twisted in the HV mill configuration (with definite passes in vertical stands).
- A continuous bar mill can have either an even or an odd number of stands. It contains three distinct mills: the roughing mill, the stretching mill and the finishing mill These three mills are roughly identified by three groups of rolls: from furnace down, these groups show decreasing barrel diameters, increasing surface hardness and decreasing yield strength - core materials going from steel to 'steel base' to cast iron.
- Definite passes have two equal axes in an x, y plane.
- In a square-into-oval deformation, the bar needs to be turned at less than 90 degrees.
- Hot size of the bar is normally taken as 1.013 times the cold size.
- Squares and rounds are intermediate passes.
- Two facing grooves form a roll pass.
- A sequence only produces definite passes.
- In a continuous bar mill, it is not necessary that the reduction must be applied after a 90^0 rotation of the bar at each stand.
- Traditional mills only use horizontal stands. The ovals are twisted to bring the long axis between the rolls. There is one deformation that needs special treatment: the square-into-oval.
- If v_1 and v_2 denote the work piece speed entering and leaving a mill stand and r is the reduction in the cross sectional area then $v_2 = v_1/ (1-r)$
- The rolling process starts from a short bar with a large section area, to obtain a long product with a small sectional area. The volume (or the weight) prior to and after the rolling process remains constant.

Rolling a 1/2-ton billet yields a 1/2-ton coil. Cross sectional area times bar length is a constant. In rolling some weight is lost with scale and crop ends.

- In a mill stand the peripheral speed of a work roll remains constant. But the surface speed at the point on the surface of the work piece increases as it passes through the contact angle until usually on exit from the bite, it exceed of the roll. The work piece exhibit forward slip.
- In continuous bar rolling, the volume remains constant so does the flow Assume that the exit bar from stand 1 has cross sectional area = 3467 sq mm and the finished round has cross-sectional area = 113 sq mm (hot bar dimensions). If the finished stand delivers at a speed of 12 mps, then stand 1 must rotate at 0.39 mps: 0.3 x 3467 = 12 x 113. In this case the constant is about 1050. If the cross sectional areas of the passes are known, the exit speeds can be calculated. There is no problem in setting the speed at each stand, as each stand has its own independent motor.
- Roll materials are cast iron , cast steel and forged steel because of their high strength and wear resistance requirements.

Determination of Tonnage Rolled per Hour

Diameter of Roll = d mm.

Effective Diameter of Roll = d_e mm

RPM of Bar being Rolled = r

[Specific Gravity of the Rolled Material] = s gms./ cu. cm.

Cross-sectional area = $\pi /4\, d^2$ sq.mm.

= $\pi /4\, d^2 / [1000 \times 1000]$ sq meters.

= $\pi /4\, d^2 / [10^6]$ sq meters.

Circumference = $\pi\, d_e$ mm.

= $\pi\, d_e / 1000$ meters

Length per minute = Circumference x RPM

= $\pi\, d_e / [1000 \,.\, r]$ meters

Length per hour = $\pi\, d_e / [1000 \,.\, r \,.\, 1/60]$ meters

= $\pi\, d_e\, r / [6 \times 10^4]$ meters

Volume per hour = Cross-sectional area x Length

= $\{\pi /4\, d^2 / [10^6]\} \times \{\pi\, d_e\, r / 6 \,.\, 10^4\}$ (meters)^3

= $\pi^2 /4\, d^2 \,.\, d_e \,.\, r / [6 \times 10^{10}]$ (meters)^3

Specific Gravity = s gms./ cu.cm

= [s ÷1000 . 1000] / [cubic cm.÷100 . 100 . 100] Tons per cu.cm.

Weight = $\pi^2 /4\, d^2 \,.\, d_e \,.\, r / [6 \times 10^{10}] \,.\, s$ Tons

$= [\pi^2 / 4 / 6 . 10^{10}] [d^2 . d_e . r . s]$ Tons.

Determination of Effective Diameter

Diameter of bar	=	d mm.
Effective diameter	=	d_e mm
Collar Diameter	=	d_c mm
Width at the Face	=	W
Area of the Cross section	=	A sq. mm.

Effective Diameter, d_e = d_c - [A/W]

Delivery Speed

Targeted Rolling Rate	=	W MT/ Hr.
Cross sectional Area	=	A sq. mm.
	=	A / 100 sq. cm
Specific Gravity	=	s gms./ cu. cm.
Tonnage per hour	=	W MT.
	=	W . 1000 . 1000 gms
Volume per hour	=	$W . 10^6 / s$ cu.cm.
Length per hour	=	$W.10^6 / s . (A / 100)$ cm
	=	$100 .10^6 . W / s . A$ cm
	=	$[100 . 10^6 W / S .A] / 100$ meters
	=	$W.10^6 / S . A$ meters
Length per seconds	=	$[W 10^6 / S. A] / 60 . 60$ meters
	=	$[10^4 . 36] / W / (S . A)$ meters
Rolling Speed	=	277.78 W / (S . A) meters / second

ROLLING & its PARAMETERS

- When a piece of metal is rolled between two rolls, the metal piece experiences both vertical and horizontal stresses caused by the compressive load from the rolls and the restrains by the portions of the metal piece before and after the material in contact with the roll respectively.
- As the rolls exert a vertical stress on the metal piece, the latter exerts the same amount of stress back onto the rolls itself. As such the rolls are subjected to elastic deformation due to this stress induced by the work piece.
- The thickness is reduced as a result of the compressive stresses exerted by the rolls and it is treated as a two-dimensional deformation in the thickness in length directions or changes its cross sectional area.
- In the deformation zone the thickness of the input metal gets reduced and it elongates. This increases the linear speed of the work piece at the exit.
- The contour of the roll gap controls the geometry of the product.

"Draught", also known as draft, is a term meant to express the reduction in cross section height / area or reduction in height in a vertical direction when compressed between two rolls.

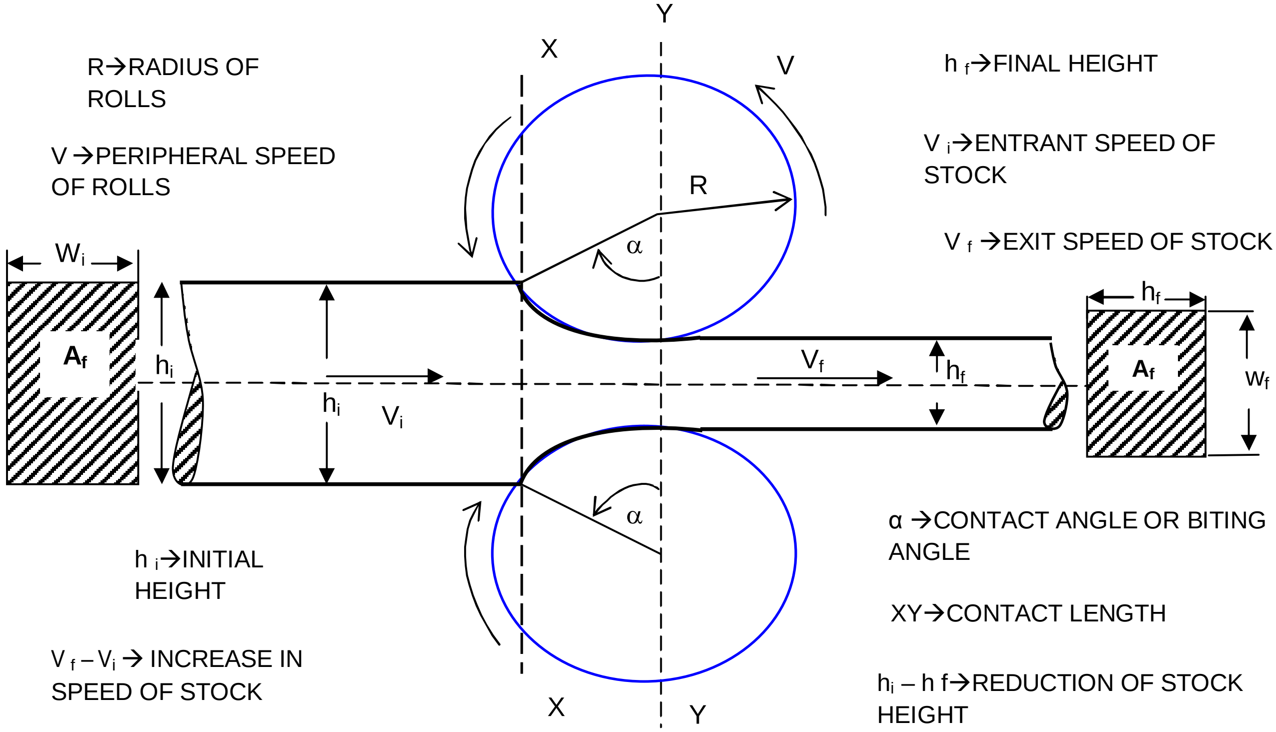
- Draft is either direct or indirect.
- Indirect draft results when the rolls exert on the stock in non-vertical direction. Basically it is a grinding action between the collars of two rolls rotating in opposite direction.
- When part of the pass profile is inclined in between the vertical and horizontal, the deformation is caused by a combination of direct as well as indirect drafting.
- Up to an inclination of 45^0 with the horizontal direct drafting predominates. However, above 45^0 inclinations the effects of indirect drafting comes in to play. Near 90^0 the deformation depends almost entirely on indirect draft.

"Elongation" in stock length is associated with reduction in area, as volume of metal leaves the rolls as enters them is equal. Elongation factor, i.e., the ratio of the final length to the initial length is always greater than unity.

"Spread"

- When steel stock is compressed between two rolls, it obviously moves in the direction of least resistance. There is not only a longitudinal flow but also some lateral flow, which is called 'Spread'.
- Rolling signifies one action but two reactions. The rolls apply a 'reduction' (vertically); this reduction produces an 'elongation' and 'spread' (sideways).
- The stock under vertical compression meets some longitudinal resistance to free elongation which assists in causing sideways spread.
- Spread is the flow of material at right angles to the directions compression and elongation.
- The coefficient of spread is the ratio between exit and entry width.
- The higher the coefficient of friction, higher is the resistance to lengthwise flow and more is the spread.
- Spread is the most difficult and complex of all the parameters in rolling to understand.
- The quantum of spread can never be worked out analytically. Neither any formula nor any method of computation is available to quantify spread.

ROLLING PARAMETERS



- Roll Designers only rely on guess estimate to overcome the problem, but accuracy of such guess work is not only extremely necessary but is needed.

In practice it is found that the following factors affect the amount of spread.

- Temperature of the work piece influences spread appreciably. Lower the temperature of steel input, greater is the spread. Similarly, higher the temperature, lesser is the spread.
- Lesser speed of rolling results in greater spread and vice-versa.
- Diameter of the working rolls plays a significant role in the guess estimation of spread. Higher the diameter of the working rolls, lesser is the spread. Similarly, lower diameter results in higher spread.
- Surface roughness, i.e., friction of the working rolls plays a note worthy part in determining spread. Rougher the roll surface lesser is the spread and smoother the roll surface more is the spread.
- Stock height and width play influences spread. Higher draft and wider stock signifies greater spread.
- When rectangular stock passes through plain rolls then the spread is "free" or "unrestricted". However, if the stock passes through grooved rolls, then the form of the pass keeps the spread within certain limits. This is known "restricted" spread.
- Because of this restricted spread the width of an entering stock is smaller than the width of the pass groove.
- It is accepted that beyond a ratio width / height = 5, spread becomes negligible.

Rolling Forces and Their Relationships

A metal bloom / slab with a thickness h_i enter the rolls at the entrance plane $x\ x$ with a velocity v_i . It passes through the roll gap and leaves the exit plane $y\ y$ with a reduced thickness h_f and at a velocity v_f**.** Given that there is no increase in width, the vertical compression of the metal is translated into an elongation in the rolling direction. Since there is no change in metal volume at a given point per unit time throughout the process,

$$\therefore b\, h_i\, v_i = b\, h\, v = b\, h_f\, v_f$$

Where, b is the width of the metal stock, v is the velocity at any thickness h intermediate between h_i and h_f

If, $h_i > h_f$**,** then $v_i < v_f$. The velocity of the metal stock steadily increases from entrance to the exit such a way that a vertical element (cross section) in the metal stock remains undistorted and in a line.

Given that $b_i = b_f$

$$h_i\, L_i / t = h_f\, L_f / t$$

Again,

$$h_i\, v_i = h_f\, v_f$$

$$v_i / v_f = h_f / h_i$$

At only one point along the surface of contact between the roll and the bloom / slab, two forces act on the metal :

A radial force P_r, and a tangential frictional force F.

If the surface velocity of the roll v_r equal to the velocity of the work piece, this point is called neutral point or no-slip point.

Between the entrance plane $(x\ x)$ and the neutral point N the work piece moves slower than the roll surface, and the tangential frictional force, F , act in the direction to draw the metal into the roll.

On the exit side $(y\ y)$ of the neutral point, the work piece moves faster than the roll surface. The direction of the frictional force is then reversed and opposes the delivery of the metal from the rolls. The location of the neutral point N is where the direction of the friction forces changes.

P_r is the radial force, with a vertical component P (rolling load - the load with which the rolls press against the metal). The specific roll pressure, p, is the rolling load divided by the contact area.

$$p = P / b\, L_p$$

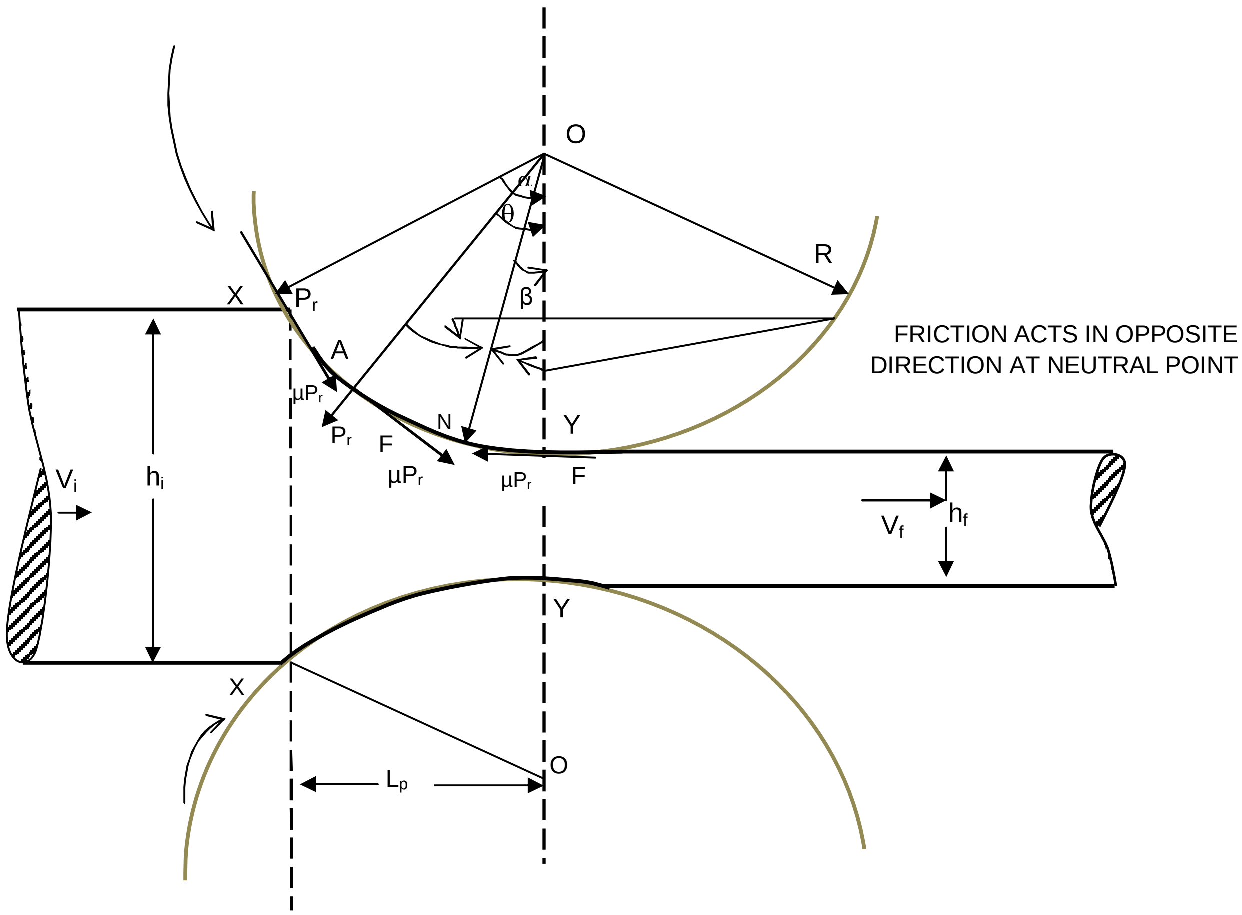
Where b is the width of the work piece & L_p is the projected length of the arc of contact.

$$L_p = [\, R\,(h_0 - h_f) - \{(h_0 - h_f)^2\} /4]^{1/2}$$

$$\approx [\, R\,(h_0 - h_f)\,]^{1/2}$$

$$\approx \sqrt{R\, \Delta h}$$

Forces in Rolling



At N POINT → $V_{ROLL} = V_{STOCK}$

Pressure during Rolling

The distribution of roll pressure along the arc of contact shows that :

- The pressure rises to a maximum at the neutral point and then falls off.
- The pressure distribution does not come to a sharp peak at the neutral point, which indicates that the neutral point is not really a line on the roll surface but an area.
- The area under the curve is proportional to the rolling load.
- The area in shade represents the force required to overcome frictional forces between the roll and the stock.
- The area under the dashed line AB represents the force required to deform the metal in plane homogeneous compression.

Roll Bite Condition

For the work piece to enter the throat of the roll, the component of the friction force must be equal to or greater than the horizontal component of the normal force.

$F \cos\alpha \geq P_r \sin\alpha$

$F / P_r \geq \sin\alpha / \cos\alpha \geq \tan\alpha$

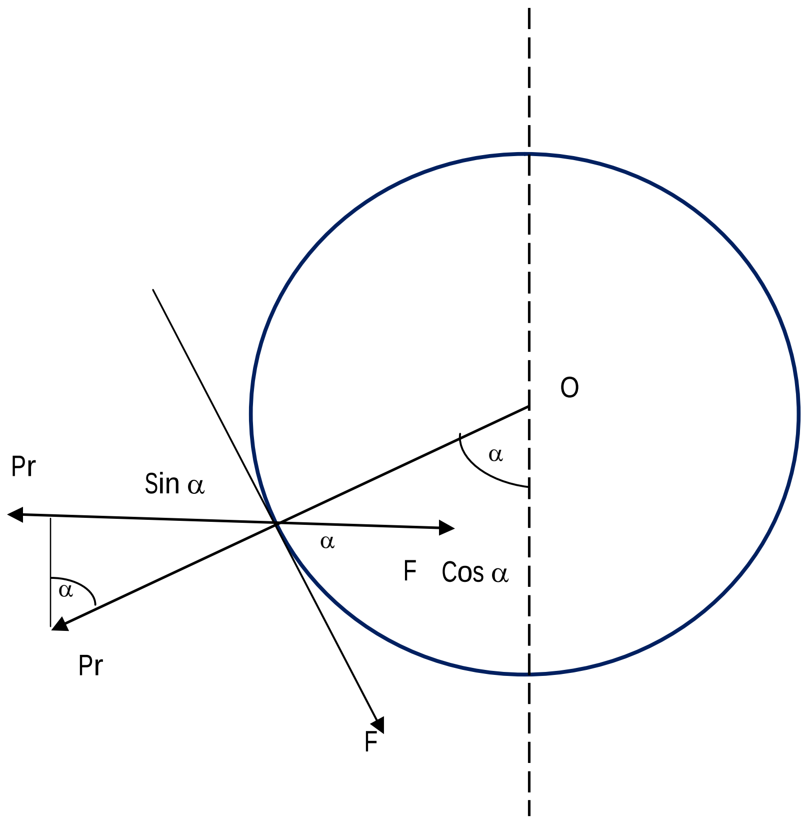
It is known that

$F = \mu P_r$ or $\mu = F / P_r = \tan\alpha$

$\therefore \mu = \tan\alpha$

F is a tangential friction force & P_r is radial force

- If $\tan\alpha > \mu$, the work piece cannot be drawn.
- If $\mu = 0$, rolling cannot occur.



F IS A TANGENTIAL FORCE

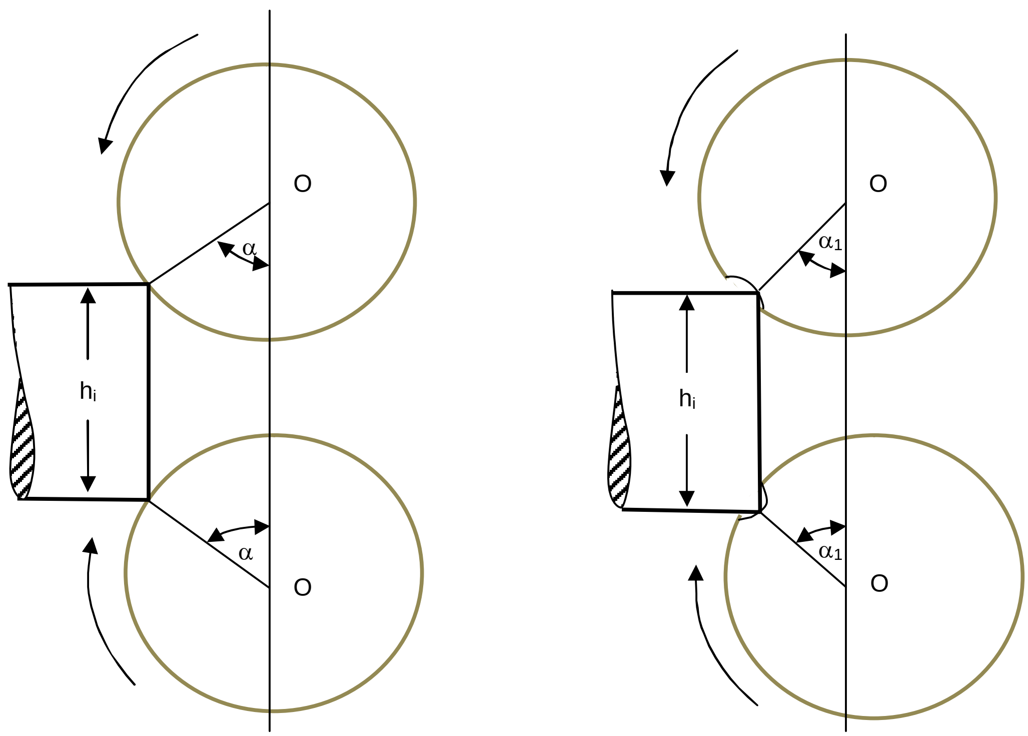
Pr IS A RADIAL FORCE

Free engagement will occur when $\mu > \tan\alpha$

To increase the effective value μ

- Groove the rolls parallel to the roll axis.
- Use bigger diameter rolls to reduce $\tan\alpha$. In practice the roll designers take the maximum biting angle as $22\frac{1}{2}^{0}$ - 24^{0}. In case the roll diameter is fixed, reduce the input height, h_i.

Grooving Decrease Angle Of Contact

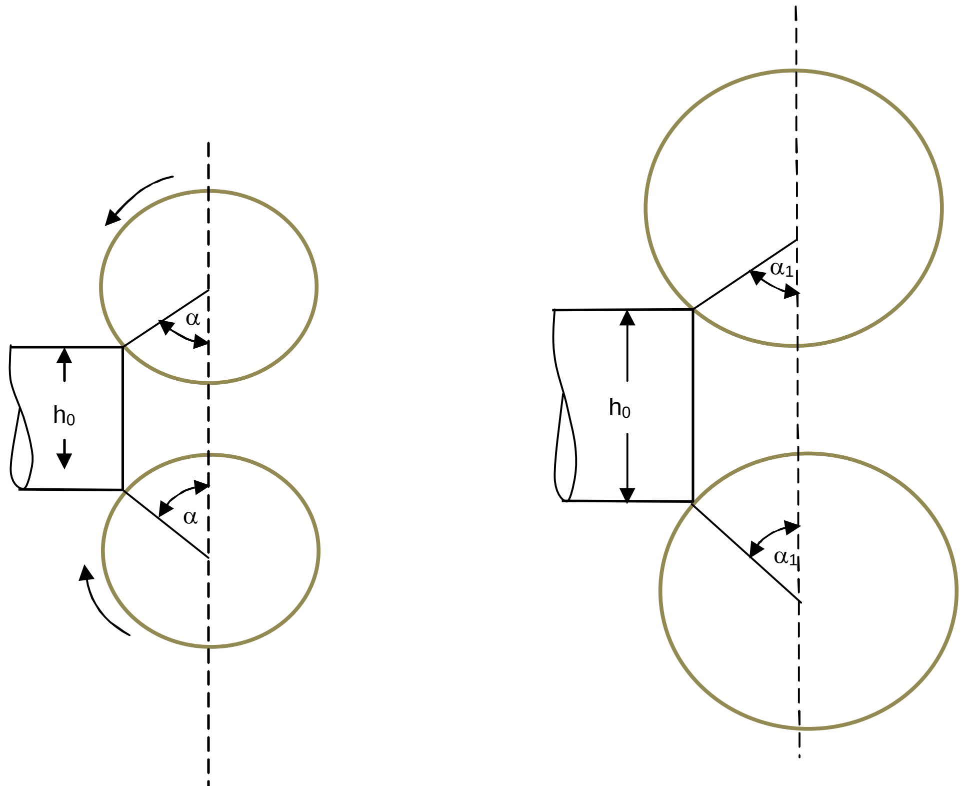


$\alpha > \alpha_1$

α **-> Contact angle before grooving**

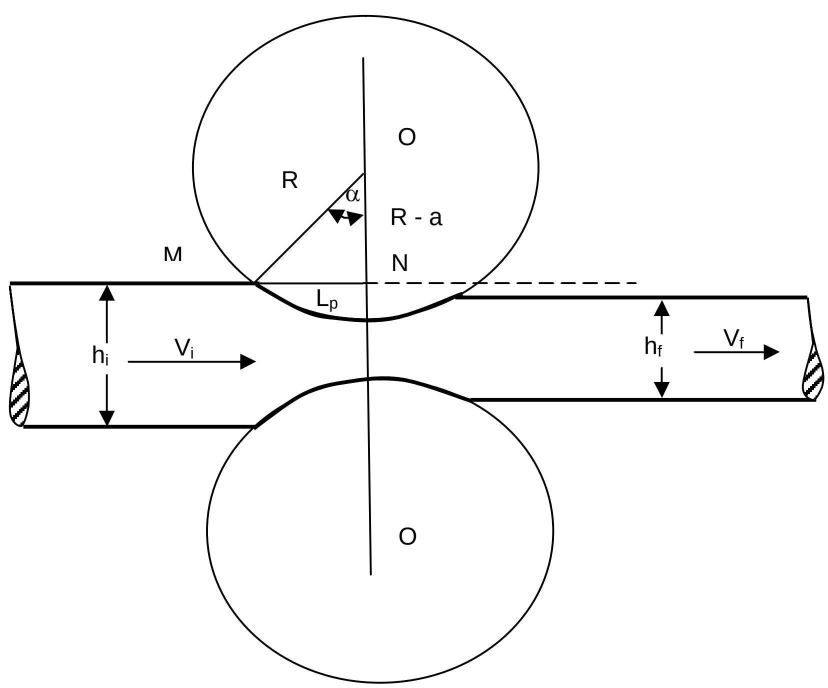
α_1 **-> Contact angle after grooving**

Increasing Diameter of Rolls Decreases Angle of Contact



$\alpha > \alpha_1$

The Maximum Reduction



The critical variables are L_p and h

From Δ MNO,

$R^2 = L_p^2 + (R - a)^2$

$L_p^2 = R^2 - (R^2 - 2Ra + a^2)$

$= 2Ra - a^2$

As a is much smaller than R, a^2 ignored.

$L_p \approx \sqrt{[2Ra]} \approx \sqrt{R\Delta h}$

Where, $\Delta h = h_i - h_f = 2a$

A large diameter roll permits a thicker work piece than a smaller diameter roll.

$\mu = \tan \alpha = L_p / [R - \Delta h / 2]$

$= \sqrt{R \Delta h} / [R - \Delta h / 2]$

$= \sqrt{[\Delta h / 2]}$

Therefore, $\Delta h_{max} = \mu^2 R$

Analysis of Rolling Load

The main variables in rolling are :

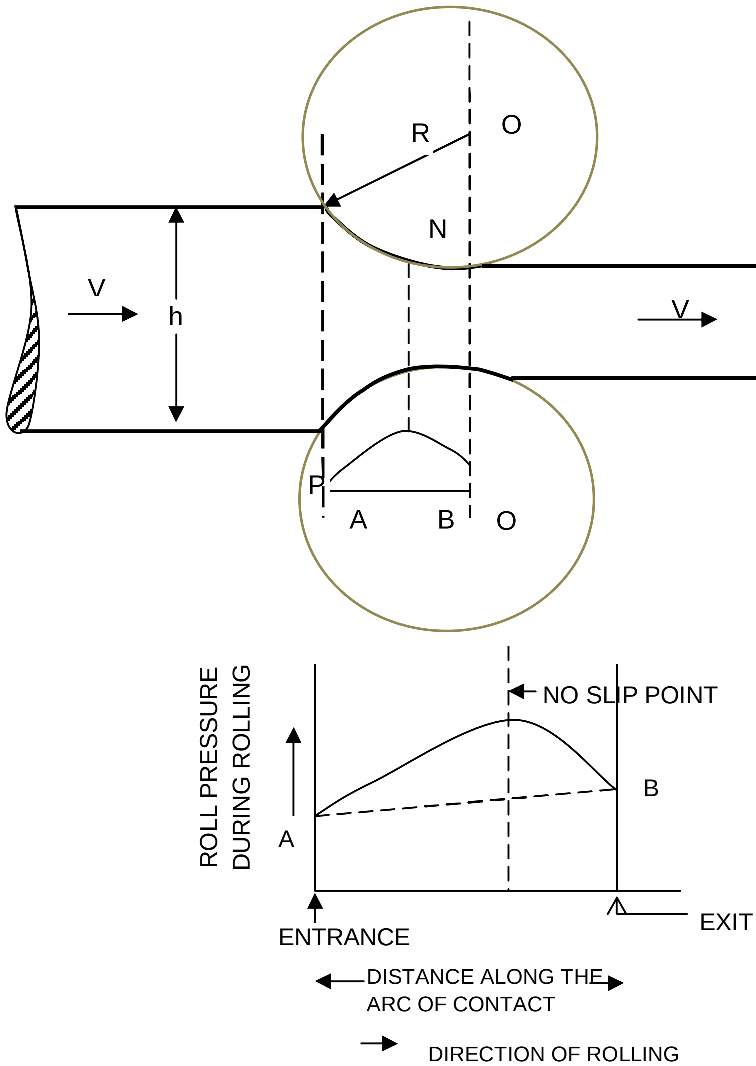
- The working roll diameter – with higher diameter of the working rolls, greater drafting is possible.
- The contact length, i.e., the biting angle is decreased by decreasing the roll radius. Lesser the biting angle, lesser is the reduction.
- The deformation resistance of the metal is influenced by metallurgy, temperature and strain rate.
- The friction between the rolls and the work piece – greater the friction higher is the drafting possible.

Friction & its Effect

- When a stock undergoes drafting, it moves further in to the roll gap and its cross sectional area is reduced.
- The roll surface speed exceeds the stock speed at the plane of entry.
- Therefore, the velocity of the stock increases as it passes between the two compressing rolls.
- The roll pressure varies along the arc of the contact angle. The peak pressure is located at the neutral point. The area beneath the curve represents roll force.
- As the bar speed increases on entry there is eventually a point where the speeds of the roll surface and the stock coincide, i.e., become equal. This point is called the "neutral point".
- Along the arc of contact or the common interface between each roll and the work piece, there is a position where the roll and work piece surface speed are equal. This position is known as the neutral

point. In the case of a rolling operation symmetrical with the pass line, the neutral points on each arms of contact lie in a vertical plane.

Friction Hill in Rolling



- At the neutral point there is neither forward nor backward frictional forces acting on the bar surface. At this point the direction of the frictional force reverses
- Beyond this point the stock speed exceeds the roll surface speed. It is seen that the stock comes out of the rolls at a speed greater than the peripheral speed of the rolls. This is known as "forward slip", "speed gain" or "extrusion effect".
- The material to be rolled is drawn by means of friction into the two oppositely rotating roll gaps.
- Frictional force is needed to pull the metal into the rolls and responsible for a large portion of the rolling load.
- High friction results in high rolling load, a steep friction hill and great tendency for edge cracking.
- The friction varies from point to point along the contact arc of the roll.
- However, it is very difficult to measure this variation in μ, all theory of rolling are forced to assume a constant coefficient of friction.

- The peripheral velocity of rolls at entry exceeds that of the work piece, which is dragged in if the interface friction is high enough.
- Hot rolling rolls are rough; the surface area has high friction so that they can grip/bite the work piece.
- Friction depends on the nature and the temperature of the material being worked and the amount of draft. In cold rolling the value of coefficient of friction is around 0.1 and in warm working it is around 0.2. In hot rolling it is around 0.4.
- Decreasing the coefficient of friction and reducing the work roll diameter move the neutral point towards the exit plane and thereby decrease the forward slip.
- When the angle of contact α exceeds the friction the rolls cannot grip and draw work piece.
- When the stock's approach is slower than the peripheral speed of the rolls then the frictional force pulls the stock in to the roll gap. But if the stock moves at higher speed than the peripheral speed, then the frictional force opposes the entry of the stock into the roll gap. Such an opposing action reduces the approach speed of the stock and thus the frictional force pulls the stock in to the roll gap.

  The position of a neutral point is dependent on :
  - Coefficient of friction along the arc of contact.
  - The diameter of the working roll.

Work

- When steel is reduced in area and elongated between the rolls, the vertical components of the forces involved in this deformation constitute the roll load, which forces the roll apart.
- This load results in mill spring.
- The total rolling load is distributed over the arc of contact in the typical friction-hill pressure distribution.

The rolling load is affected by many variables :

- A decrease in temperature of stock increases the rolling load.
- The carbon content and the alloying elements of the steel affect the yield stress. Hence with the increase of carbon content and alloying elements there is increase in the rolling load required to deform such steel.
- An increase in the rolling speed adversely affects the deformation rate and increases the working load.
- An increase in the diameter of the rolling rolls increases the length of the arc of contact and the biting angle. Therefore, more reduction is possible. Thus the rolling load increases.

Rolling Load

However, the total rolling load can be assumed to be concentrated at a point along the act of contact at a distance a from the line of centers of the rolls.

Ratio of the moment arm a to the projected length of the act of contact L_p can be given as

$$\lambda = a / L_p = a / \sqrt{R \Delta h}$$

For hot-rolling λ is 0.5.

During one revolution of the top roll the resultant rolling load P moves along the circumference of a circle equal to $2 \pi a$. Since there are two work rolls, the work done $W = 2(2\pi a) P$

The roll force depends on the draft and the contact length. Therefore, reducing the roll radius will reduce the roll force.

Torque

- Torque is the measure of the force applied to produce rotational motion. Roll torque, i.e., power required for rolling increase with increase in quantum of roll work, contact length and roll diameter.
- The torque in rolling is estimated by:

$$T = 0.5 \times F \times L$$

Where:

T: Torque (N.m)

F: Roll Force

L: Contact length

The torque M_T is equal to the total rolling load P multiplied by the effective moment arm a. Since there are two work rolls, the torque is given by $M_T = 2 P a$

The torque and power depend on the roll force and contact length. Therefore, reducing the roll radius decreases both the torque and power.

Power

- Power is applied to a rolling mill by applying a torque to the rolls.
- Power depends on the roll force and contact length.
- The power also depends on the rotational speed of the rolls, and therefore, reducing the rolls RPM will reduce the power.
- Reducing the quantum of draft decreases the power required for rolling.
- The power required to drive the two rolls is calculated as follows:

$$P = 2\pi \times N \times F \times L$$

Where,

P: Power (in J/s =Watt or in-lb/min)

N: Rolls rotational speed (RPM)

F: Roll Force

L: Contact length

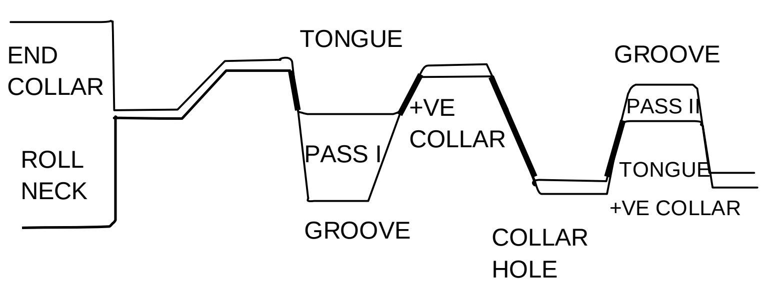
Power is spent mainly in four ways:

- The energy needed to deform the metal.
- The energy needed to overcome the frictional force.
- The power lost in the pinions and power-transmission system.
- Electrical losses in the various motors and generators.

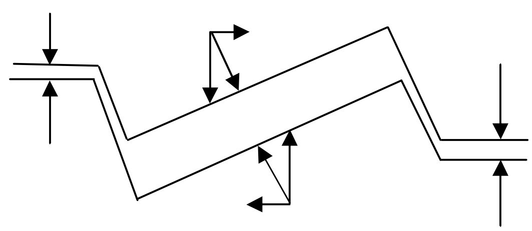
Since power is defined as the rate of doing work , i.e., 1 W = 1 J s -1, the power (in watts) needed to operated a pair of rolls revolving at N Hz (s-1) in deforming metal as it flows through the roll gap is given by $W = 4\pi aPN$ Where P is in Newton and a is in meters.

Hot-Rolling in Grooves

- ‘Stand’ refers to a set of rolls, supported by ‘bearings’ located in the ‘chocks’, which slide within the ‘housing’. The rolls are ‘opened’ or ‘closed’ by turning the ‘screws’. Two facing grooves form a ‘roll pass’. The distance between the barrels of two rolls is called the ‘nominal roll gap’ or ‘theoretical roll gap'.
- In slab / flat rolling the peripheral speed is identical and constant across the roll face. In rolling with groove such is not the case. The bottom of a groove will exhibit a tangential speed less than the tongue so the forward slip is different for different locations on the same cross section. In nonsymmetrical passes, this leads to a tendency for the work piece to curl upwards or down wards. This necessitates the use of stripper guides to strip the work piece from the grooves.
- Definite passes have two equal axes in an x, y plane, e.g., squares, rounds. Intermediate passes have one axis larger than the other one, e.g., rectangles – box, diamonds and ovals).
- A bar from definite pass into one intermediate pass or a bar from intermediate pass into one definite pass configures a ‘deformation ’, e.g., a square into an oval pass, or an oval into a square pass. A deformation can produce any type of bar. A definite bar into two passes (an intermediate pass followed by a definite pass, configures a ‘sequence ’. A sequence only produces a definite bar.
- For rolling flats/slabs, the rolls are crowned to ensure that the desired geometrical shape of the roll gap is maintained during rolling. Crowns are provided to compensate for the bending of the rolls caused by the rolling forces arising out of nonuniform thermal expansion of the rolls.
- In slab / bloom rolling the work rolls are cylindrical. However, in section rolling, the cross sectional geometry of the work piece is established by the use of grooves cut into the pair of work rolls in each stand. These grooves are known as passes.
- Matching grooves made in both rolls of a set constitute an open pass.
- Uniformity in reduction on all parts of the section is the fundamental principle of roll design of complicated and asymmetrical shaped profiles.
- Any uniformity in reduction due to the difference in bloom shape and product shape occurs in the early forming passes.
- The tendency of twisting is less evident at this early stage when the steel is more malleable due to the higher temperature and the cross sectional area is also greater.
- Perfectly parallel sides at 90^0, in a box pass would result in the pass wear and difficulty in extracting the work piece from the pass. Such passes are tapered to near about 5^0 to facilitate easier exit of the work piece and dropping of the broken scales as a result of mechanical pressure.



- ❖ A pass made by a projection on one roll fitting in to a groove on the mating roll is called a closed or tongue & groove pass.
- ❖ Where both sides of the material in a roll groove are in contact with a different roll, the groove is designated as live hole.
- ❖ Direct draft is a reduction in height in a vertical direction. In indirect drafting the rolls exert pressure on the rolling stock in a non-vertical direction.
- ❖ Indirect rolling is a grinding action between the collars of different rolls.
- ❖ When a part of the profile lies completely in one roll, no grinding action, i.e., indirect drafting is possible.
- ❖ However, where a deep groove is cut into one roll, the hole is known as a dead groove.
- ❖ That part of the groove is called "dead", as material does not flow easily in such deep groove.



- ❖ In a tilted pass there is no side working of the work piece. It is subjected to shearing forces as the material emerges out of the rolls. Under such condition of the rolling pass, passage of work piece through rolls is known as "indirect" rolling. In such rolling action there is considerable side thrust produced. Rolling in such tilted passes sometimes result in either over or under filling.

The Principles of Cooling :

- Rolls change temperature all the time. There is considerable variation in the surface temperature.
- A too high thermal gradient increases the risk of roll breakage (thermal stress).
- Heat should not penetrate the roll and therefore, the roll surface should be cooled as soon as possible at the exit side of the rolling gap.
- The cooling water must never rebound of the roll surface.
- If the flow of cooling water is interrupted, there is chance of roll breakage due to thermal stress.
- Insufficient water used increases the roll temperature until it exceeds 100° C on the surface, when the heating up process accelerates resulting in unstable rolling conditions.
- Too much water should not be a problem. Over cooling may result in roll surface material becoming more bristle and have a negative influence on the maximum bite angle possible.
- More water must be supplied to the earlier passes than to the finishing passes.
- In case of flat products, more cooling water concentrated in the centre part of the rolls than on the edges.
- More water is applied to the grooves and anti collars of section mill rolls than to the rest portion of the roll.
- When rolling non-symmetrical sections there are high axial forces which have to be compensated by the rolls. The collars which take these axial forces are highly loaded and stressed and show significant

wear. The friction areas between the roll is should be lubricated, not by oil but by some grease of low viscosity (like graphite)

Quality of Rolled Product

- The strength and the hardness of the material are a function of the chemical composition and the rate of cooling after hot rolling.
- The higher is the carbon and other alloying elements higher are the strength and more is the hardness.
- The hardness of hot rolling is generally lower than that of cold rolling and the required deformation energy is lesser as well.
- Increase of cooling rate increases hardness and strength.
- Hot rolled metals generally have little directionality in their mechanical properties and deformation induced residual stresses. However, in certain instances non-metallic inclusions will impart some directionality and work pieces less than 20 mm thick often have some directional properties.
- Non-uniformed cooling induces a lot of residual stresses, which usually occurs in shapes that have a non-uniform cross-section, such as beams, channels and rails.
- While the finished product is of good quality, the surface is covered with mill scale, which is an oxide that forms at high-temperatures. It is usually removed via pickling , which reveals a smooth surface.
- Dimensional tolerances are usually 2 to 5% of the overall dimension. Hot rolled mild steel seems to have a wider tolerance for amount of included carbon than cold rolled.
- Hot rolled is less costly.
- To achieve the best possible quality rolled products it is necessary to keep the rolling process and all parameters as constant as possible.
- Every variable should be under control as required by quality assurance.

During hot rolling (whether flat/ sections) every parameter is changing:

- The rolled material varies in temperature and cross-section from pass to pass.
- Heat is transferred to the rolls which gain heat.
- During rolling stoppage times, the roll surface cools down.
- The surface structure of the rolls change due to wear and other influences during each campaign.
- Quality aspects greatly depend on surface temperatures and temperature gradients.
- Only high tech rolling mills have the capability to compensate for some of the variations.
- To stabilize the hot rolling process the rolls are cooled.
- It takes some time to reach what are considered stable conditions in rolling schedules.
- Longer stoppage times upset the applecart.

Physical Metallurgy of Hot Rolling

- Hot rolling, due to recrystallization, reduces the average grain size of a metal while maintaining an equiaxed microstructure where as cold rolling will produce a hardened microstructure with unidirectional grains.
- As the rolling process breaks up the grains, they recrystallize maintaining an equiaxed structure and preventing the metal from hardening.

- Hot rolled material typically does not require annealing and the high temperature prevents residual stress from accumulating in the material resulting better in better quality.
- Since the crystal structures are formed after the metal is worked, this process does not itself affect its micro structural properties.

Mechanical Properties of Rolled Steel is a function of:

- Chemistry of metal.
- Reheat temperature.
- Rate of temperature decrease during deformation.
- Rate of deformation.
- Rate of deformation.
- Total reduction.
- Recovery time.
- Recrystallisation time.
- Subsequent rate of cooling after deformation.

Defects from Cast Ingot before Rolling

- Porosity, cavity, blow hole occurred in the cast ingot will be closed up during the rolling process.
- Longitudinal stringers of non-metallic inclusions or pearlite banding are related to melting and solidification practices.
- In severe cases, these defects can lead to laminations which drastically reduce the strength in the thickness direction

Defects in Rolled Products

Surface Defects : There are six types of surface defects:

- **Lap :** This type of defect occurs when a corner or fin is folded over and rolled but not welded into the metal. They appear as seams across the surface of the metal. Laps due to misplace of rolls can cause undesired shapes.
- **Mill-shearing :** These defects occur as a feather-like lap.
- **Rolled-in scale :** This occurs when mill scale is rolled into metal.
- **Scabs :** These are long patches of loose metal that have been rolled into the surface of the metal.
- **Seams :** They are open, broken lines that run along the length of the metal and caused by the presence of scale.
- **Slivers :** Prominent surface ruptures.

  - Surface defects arise easily in rolling where high surface to volume ratio.
  - Grinding, chipping, etc., of defects on the surface of cast ingots or billets are recommended before being rolled.
  - Flakes or cooling cracks along edges result in decreased ductility in hot rolling such as blooming of extra coarse grained ingot.
  - Scratches due to handling.

- Variation in thickness due to deflection of rolls or rolling speed.

The **inputs** in the hot rolling process :

- Reheated slabs and blooms / billets at about 1,150°C
- Water (for descaling, cooling,)
- Cooling water closed loop
- Energy for the drives
- Oil and lubricants
- Energy for reheating. Possible fuel types: Gas & Oil
- Refractory

The **outputs** in the hot rolling process :

- Crops, cobbles, scrap ends and samples, metallurgical and rolling rejections
- Waste water (loaded with scale and oil).
- Mill-scale (oil-free and oily). Normal mill scale is relatively coarse, with 85 to 90% of the constituent particles >0.15mm. The iron content is about 70%.

Water

- Water is a necessary input, without which rolling is not possible. It is used for temperature control, direct and indirect cooling, descaling and scale transport.
- As the hot stock comes in contact with the rolling rolls, the temperature of the latter rises and continues to increase as further rolling takes place.
- At high temperature elongation of the steel rolls takes place in all directions. Moreover, considerable heat is produced during the rolling processes; water also serves to maintain the temperature of the steel rolls.
- Cooling water is sprayed on the rolls during hot rolling to prevent distortion and to reduce erosion of the roll surfaces.
- Pass / rolling grooves get out of proportion and distorted when they become hot.
- Hot scales get stuck in the rolls and acts as a lubricant posing difficulty in drafting.
- With rise in temperature, the strength of the rolls decreases and with identical drafting there may be a breakage of the rolls.
- The temperature rise of the rolling neck cause the roll neck bearing to turn hot and the hot neck bearings may cease at any juncture.
- When steel is heated to the high temperature desired for hot rolling, its surface is oxidized and hard scale is formed.
- If not removed before rolling, this scale is rolled into the steel causing surface defects.
- Scale is removed by spraying water under pressure on the steel immediately before it enters the rolls.
- Scale thus removed is flushed to a scale pit from where it is recovered for use.
- Because much fine scale passes on to these pits, the spent cooling water is treated in settling basins or clarifiers before reuse.
- Descaling is done after cogging and within the finishing train, as scale is formed during the rolling process at elevated temperatures above 1,000°C due to the deformation work.

- The process water used for descaling directly after the furnace is usually oil free.
- The same used for descaling within the hot rolling section contains oil because of bleeding.
- As the two waste water streams are usually mixed, the result is one waste water stream containing scale and oil.
- The scale load is easily separated from the waste water. As the oil content of this share is usually sufficiently low, water is easily recycled to metallurgical processes.
- Within the rolling train it is used for cooling the rolls and the work piece.
- Descaling is required in order to prevent quality defects of the work piece.
- The scale arising within the reheating furnaces has to be removed before the stock enters the rolling trains.
- In hot roughing rolling mills descaling is usually performed by high pressure water jets or by scale breakers or by a combination of both. Water jets break the scale layer through the high kinetic energy of an impinging water jet. The detachment of the scale layer through shrinkage of the parent metal and scale is caused by shock quenching, the blasting-off of the scale through explosive type vaporization of the water drops underneath the scale layer and the flushing away of the detached scale through an inclination of spray jets to the surface.
- Direct and directed cooling is necessary in order to obtain the desired metallurgical properties of the work piece. After the last stand of drafting, water cooling serves in obtaining specific metallurgical properties.

Quenching

- The rolling process is completed generally at a temperature of 30° C - 50° C above A_3 or A_1.
- Then very fast cooling (in water or oil) is carried out with the cooling rate exceeding a critical value. The critical cooling rate is required to obtain non-equilibrium structure called martensite. During fast cooling austenite does not transform to ferrite and pearlite by atomic diffusion.
- With the quenching-hardening process the speed of quenching can affect the amount of marteniste formed.
- This severe cooling rate is affected by the component size and quenching medium type (water, oil).
- The critical cooling rate is the slowest speed of quenching that will ensure maximum hardness (full martensitic structure)
- Martensite is a supersaturated solid solution of carbon in α-iron (greatly supersaturated ferrite) with tetragonal body centered structure. Martensite is very hard and brittle and has a “needle-like” structure.
- Kinetics of martensite transformation is understood from the TTT diagrams (Time –Temperature - Transformation).

APPARENT PROBLEMS, POSSIBLE REASONS & FEASIBLE RECTIFICATION

PROBLEMS	POSSIBLE REASONS	FEASIBLE RECTIFICATION
Black smoke emerging from the chimney.	• Fuel gas input to the furnace is in excess of the combustion air. • Lesser amount of combustion air (oxygen) input to the furnace.	• Reduce the amount of fuel gas input. • Augment the quantum of combustion air input.
Thick scales covering the heated billets coming out of the reheating furnace.	• Disproportionate combustion air input to the furnace. • Extended period of stay inside the furnace at a high temperature.	• Cut the combustion air input, i.e., less O_2 availability for oxidation of steel. • Diminish combustion air and fuel gas inputs to the furnace when rolling is suspended for a long period to decrease both O_2 & temperature.
Hot billets stick together in the hearth area of the furnace, preventing one by one smooth delivery from the furnace,	• Overheating and extended period of stay in the very hot zone of the furnace when the normal rate of rolling is disturbed.	• To reduce fuel and air when the disturbance is expected to last for some time.
Billets either not entering or there is difficulty in entering in the roll grooves.	• Entry box out of alignment with the rolling grooves. Both or any one guide has either opened out so that bloom is knocking at the collar or guides have closed in. • Rolls loose, out of square or not in level.	• Entry box to be set accurately, i.e., in alignment with the rolling grooves. • Rolls to be tightened / squared / leveled.

	• Billets entering roll groove are not having proper heat - lower temperature / lesser soaking.	• Temperature of the furnace and the soaking time in the furnace to be increased accordingly.
Billet delivery from the rolled passes is abnormal - materials skewing / bending / delivering upwards or downwards.	• Delivery box not set properly as per the rolling grooves. • Rolls loose, out of square or not leveled. • Insufficient heat of the billets being rolled – lower temperature / soaking.	• Delivery box to be properly set as per the rolling grooves. • Rolls to be tightened / squared / leveled. • Both appropriate temperature and soaking of billets to be ensured.
Billets getting stuck at the forming pass.	• Overheating of the billets inside the furnace. • Absence of proper ragging mark to increase friction.	• Uniform heating of the stock to be ensured. • Welding spots may be resorted to.
Stocks failing to enter the rolling pass of the subsequent stands.	• Stock delivering from the previous pass is either over size &/or under or over twisted. • Rolls in previous stand have become askew. • Entry guides of the subsequent stands have shifted and become out of alignment. • Rolls loose, out of square or not leveled.	• Under or over twisted delivery from the previous pass to be corrected by appropriate adjustment of the twist guides. Delivery size of stock form the previous pass must be checked / adjusted. • Rolls in the previous stand to be aligned. • Entry guides to be correctly aligned. • Rolls to be tightened / squared / leveled.

	• Rolling stock at lower temperature causing biting problem. • The front end of the work piece is split. • Entering rolling stock is oversized – either due to higher mill spring of earlier groove or trying to roll bar at lower temperature & insufficient soaking.	• Both proper temperature and soaking of billets to be ensured. • To be detected & taken out before it enters the succeeding pass. • Mill spring set correctly & rolling stock with appropriate temperature and aptly soaked.
Roll neck bearings running hot.	• Insufficient cooling / lubrication. • Too much tightening of the bearings against the roll collar. • Excessive rolling speed when the heat accumulated does not get dispersed.	• Proper cooling to be immediately ensured. • Temperature of the roll neck bearings to be checked from time to time so that so that these do not run hot. • Hot bearings scores roll necks to propagate early failure of the next bearings used. • May develop thermal cracks in the roll necks causing early failure. • Proper tightening of the bearings against the roll collar to be ensured.
Quick wearing out of the roll passes – less pass life in terms of lower tonnage rolled.	• Insufficient cooling of the rolling grooves. • Insufficient heat of the materials being rolled – lower temperature and lower soaking.	• Proper cooling of the roll passes to be immediately ensured. • Proper temperature of materials being rolled to be ensured.

	• Higher drafting in the pass in question resulting from the wear out of the previous pass.	• The dimension of the material entering and coming out of the pass to be checked from time to time. • Tension of the stripper guides should not very high. • Proper material of the stripper guides to be ensured.
Breakage of connecting couplings.	• Insufficient heat of the materials being rolled – lower temperature and lower soaking causing increase in the torque while rolling. • Casting defects, e.g., blow holes, cracks, etc.	• Proper temperature & soaking of rolled materials to be ensured. • Checking of the coupling boxes castings before putting in to the mill for use. • Proper feeding of the material to be ensured so that there is no sudden end thrust.
Roll breakage from the journal.	• Insufficient cooling / lubrication roll neck bearings, resulting in the roll neck to run very hot. • Casting defects, e.g., blow holes, cracks, etc.	• Proper cooling of the roll neck bearings to be immediately ensured. • Checking of the roll castings before putting in to the mill for use.
Roll breakage from the barrel.	• Over drafting.	• Drafting to be as per norm. • Proper temperature &

	• Insufficient heat of the materials being rolled – lower temperature and lower soaking. • Insufficient cooling of the rolling groove.	soaking of rolled materials to be ensured. • Proper cooling both from the top and bottom f the roll barrel particularly the rolling grooves to be immediately ensured.
ROUNDS Bar delivering from finishing pass twisting in clockwise or anticlockwise manner.	• For clockwise rotation of the bar the top roll is out of square towards left. • For anticlockwise rotation the top roll is out of square towards right. • Finishing pass entry box guides may be either opened out, worn out or out of level. • Rolls out of square at the oval pass.	• Shift top roll from left to right. • Shift top roll from right to left. • Finishing pass entry box guides to be checked and set properly if found open or out of level.
Ribs on both sides of the round.	• Dimension of the minor axis of oval entering the round finishing groove is large.	• Reduce dimension of the minor axis of the oval being delivered from the leading groove. • If this action fails, reduce dimension of square groove preceding the oval.
Rib on any one side and on the other side the dimension is less than desired, i.e., empty/under full.	• Finishing pass entry box guide has opened out on the side rib has appeared and closed in on the other side.	• Finishing pass entry guide is to be closed in on the side rib has appeared and opened out on the other side.

Dimension is less than desired, i.e., empty/under full on both sides of the round.	• Minor axis oval entering the round finishing pass is less in dimension.	• Increase the dimension of the minor axis of the oval from the leading groove. • If this action fails, increase dimension of square groove preceding the oval groove.
Rolled weight in Kg. /meter is either more or less than the standard.	• Cross sectional area of round rolled is either more or less.	• In case the round rolled is on lighter side, reduce the drafting in the finishing pass. If on the heavier side, increase the draft in the finishing groove.
ANGLES **Both the flanges of the angle (leg lengths) less than the standard dimension.**	• Material delivered to the finishing groove is much less either from the leading groove or earlier groove/grooves.	• Increase the dimension of material delivered to the finishing groove. • Incase this increase is not enough; enlarge the dimensions of the previous groove/grooves one at a time.
Both the flanges of the angle (leg lengths) more than the standard dimension. (Fins appear in Gothic roll pass design but not so in butterfly design)	• Material delivered to the finishing groove is much more either from the leading groove or earlier groove/grooves.	• Reduce the dimension of material delivered to the finishing groove. • Incase this reduction is not enough; reduce the dimensions of the previous groove/grooves one at a time.
One (flange) leg length is less/short, while that of the other is more. **(Fins appear in Gothic**	• Entry guide (on the side the flange is short) has shifted in covering a part of the pass groove.	• Entry guide in question to be shifted out so that it does not come in the way pass & cover any part of the groove.

roll pass design but not so in butterfly design)		
Thicknesses of angle flanges are not equal.	• Top and bottom roll have become crossed & are out of alignment sideways / out of level.	• The two rolls in question to be repositioned / realigned and/or correctly leveled.
Angles rolled have blunt / rounded apex instead of being sharp & pointed.	• Adequate drafting is not being provided in the apex region of the finishing pass. Less material at apex may be a deficiency in original design.	• Sufficient amount of material to be brought from the leading pass and provide for increase in drafting in the apex region of the finishing pass.
Lap at the toe of the flanges. (This can happen in any of the grooves where openings are there at the toe).	• Extra material flowing out from the openings at the toe getting folded and subsequently rolled out to form lap.	• Reduce quantity of material
Apex of angle is being grazed in one side, losing its sharpness.	• One side entry guide has moved out in the finishing groove & the bar while being rolled falls over and its apex is grazed by a flange of the angle.	• Close in the entry guide that has moved out. The bar while being rolled in the finishing groove does not fall over and its apex is not grazed by the flange of the angle.
Wavy / negative flange length.	• In gothic design the work piece is subjected to heavy forming passes. By design there is enormous disparity in dimension between the toe area and the inside curved area of the angle. When the work piece is subsequently drafted there is large difference in the metal flow in lengthwise directions - metal flow in the toe area is much less compared to the inside area. Consequently toe area material is	• Maximize drafting in the initial passes and reduce drafting in the later passes • This will reduce the disparity of the drafting between the web and the flanges.

	forced along in lengthwise direction by the curved area material flow. Thus there is shortfall of material flow in the downward toe area.	
Rolled weight in Kg./meter is either more or less than the standard.	• Cross sectional area of the angle rolled is either more or less.	• In case the angle rolled is on lighter side, reduce the drafting. • If rolled on the heavier side, increase the draft in the last pass.
CHANNELS **Both flanges of the channel (leg lengths) less than the required dimension.**	• Channel is rolled by direct drafting of the web and indirect drafting of the flanges. Closing the gap of the roll groove results in comparatively much more direct drafting in the web and much less indirect drafting in the flanges. Due to this considerable inequality, when the work piece is drafted there is large difference in the increase of material in the lengthwise direction, i.e., the increase in length between two areas differs to a great extent when rolled. Flange material is pulled along with by the web material in lengthwise direction. Thus there is shortfall in material flow in the depth direction in the flanges.	• Increase the drafting in the earlier passes & reduce drafting in the finishing passes to reduce the inequality and -thus do away with the pulling action by the web on the flanges. • Reducing drafting in the end pass may result in loss of / indistinct brand mark. A balance has to be struck.
Wavy / negative flange length.	• Same as above.	• Same as above.

Channels with under fill on the web at one/or both the junctions of web and flanges instead of being sharp.	• As a result of direct drafting of the work piece in the finishing pass, spread of material occurs. When the finishing pass web width is more than what is needed to accommodate the spread of web width, under fill on the web takes place. • The angle between the web and the flange in the finishing pass is very close to 90^0. As the finishing passes wear out and the rolls are dressed, the web width increases after every such turning. • Correspondingly the angle between the web and the flange in the leading pass is much more than 90^0. As the leading passes wear out and the rolls are turned, the web width does not increase after every such dressing.	• Increase draft in the leading pass and reduce draft in the finishing pass to limit the spread of the web. • Be careful while reducing the finishing pass draft so the brand mark on the finished bar does not get lost / indistinct. • While selecting the combination of passes, choose the finishing pass with lower web width & the leading pass with larger web width. • While dressing rolls take maximum 'off', i.e., reduce the diameter to the highest limit to dress out finishing pass with smaller web width. • While roll dressing and subsequent pass grooving try to make the most excellent combination of smaller finishing web width with larger leading pass web width.
Lap at the flanges.	• For feeding into the forming pass, blooms/slabs are rolled in box pass design with opening near about the middle are prone to have laps. Openings are provided in grooves for flow of excess metal. Openings are immediately followed by closed walls in the next pass to roll out the extra material, coming out of the opining. • Some extra metal (more than anticipated) flow out. This amount cools down quickly. The cold	• Accommodate the total draft into the number passes provided with care so that the overflow from the openings of any of the passes is beyond the limit to rolled out in the length direction.

	overflows cannot be rolled out & is subsequently folded in & rolled into the flanges as laps.	
Rolled weight in Kg./meter is either more or less than the standard.	• Cross sectional area of the channel rolled is either more or less.	• In case the channel rolled is on lighter side, reduce the drafting. Reducing drafting in the end pass may result in loss of / indistinct brand mark. A balance has to be struck. If rolled on the heavier side, increase the draft in the finishing pass. Be cautious because while doing so it may result in short/wavy flanges. with lower web width
Joists / Beams **Both flanges of the Joists / beams (leg lengths) less than the required dimension.**	• Beams are rolled by direct drafting of the web and indirect drafting of the flanges. Closing the roll groove results in comparatively much more drafting in the web and much less in the flanges. Due to this massive disparity, when the work piece is drafted there is large difference in the increase in the lengthwise direction, i.e., the increase in length between the web and flanges differs to a great extent when rolled. Flange material is pulled along with by the web material in lengthwise direction. Thus there is shortfall in material flow in the depth direction in the flanges.	• Increase the drafting in the earlier passes & reduce drafting in the finishing passes to stop the pulling action by the web on the flanges. • Reducing drafting in the end pass may result in loss of / indistinct brand mark. A balance has to be struck.
Wavy / negative flange length.	• Same as above.	• Same as above.

Lap at the flanges.	• For feeding into the forming pass, blooms/slabs are rolled in box pass design with opening near about the middle are prone to have laps. Openings are provided in grooves for flow of excess metal. Openings are immediately followed by closed space in the next pass to roll out the extra material, coming out of the opining. • Some extra metal (more than anticipated) flow out. This amount cools down quickly. The cold overflows cannot be rolled out & is subsequently folded in & rolled into the flanges as laps.	• Accommodate the total draft into the number passes provided with care so that the overflow from the openings of any of the passes is not beyond the limit to rolled out in the length direction.
Rolled weight in Kg./meter is either more or less than the standard.	• Cross sectional area of the beam rolled is either more or less.	• In case the beam rolled is on lighter side, reduce the drafting. Reducing drafting in the end pass may result in loss of / indistinct brand mark. A balance has to be struck. • If rolled on the heavier side, increase the draft in the finishing pass. Be cautious because while doing so it may result in short/wavy flanges.