Chapter 2

Process Description

2.1 Introduction

In this chapter a general process description of the steel manufacturing process is presented. This is done in order to show where the hot rolling mill fits into the steel manufacturing process. In this dissertation the focus falls on a Steckel Hot Rolling Mill process, and the practical operation of a hot rolling mill process is described according to how a Steckel Rolling Process is operated. The mechanics of the rolling process is also discussed, and the reader is referred to the appendix for the definitions of some rolling terms that are used in this chapter and throughout this dissertation.

2.2 General Production Route

The production of steel can be characterized into three areas where processing takes place namely, Iron Manufacturing, Steelmaking and Rolled products [21].

Iron making or manufacturing can be defined as the extraction of metallic iron from iron ore via a reductant such as coal or natural gas. Application of this principle gives rise to a number of possible processing routes, of which only a few are implemented in industry. In the Blast Furnace Route, coke is manufactured from coal via the coking plant, and sinter (partially reduced iron ore) is produced by a sinter plant using fine ore and dolomite in a reducing atmosphere. These, along with pulverized coal, dolomite and iron ore are the raw materials used by the blast furnace to produce pig iron. The pig iron is produced in a molten state and still contains many impurities. The next processing step of the pig iron is conducted at the steel plant.

The Direct Reduction Route has two common types of direct reduction furnaces and the product of the direct reduction process is referred to as DRI (direct reduced iron). Firstly a vertical shaft furnace where pelletized ore is fed to the top of the furnace, whilst a reducing gas, such as reformed natural gas, is fed in a countercurrent fashion from the bottom. Reduction of the particles takes place during retention inside the furnace and the reduced iron particles with high metallic iron content are extracted at the bottom.

The second type of direct reduction process is a rotary kiln process. Coal, iron ore and a desulphurising agent such as dolomite are fed countercurrent, combusting the carbon monoxide product above the solids bed to provide heat. The degree of metallization is also determined by the retention time in the kiln. After the product is cooled, it is separated into metallic and non-metallic fractions.

Steelmaking can be defined as the purification of the products of ironmaking to yield desired steel grades. Two routes for steelmaking exists in the industry namely the the Basic Oxygen Furnace (BOF) Route and the Electric Arc Furnace (EAF) Route.

In the BOF Route, Pig-Iron is transferred from the blast furnace to the BOF. DRI and scrap metal are introduced along with various fluxes and oxygen as required. The main reaction in the process is oxidation of excess carbon. From the BOF, the molten steel is tapped into a ladle and taken to the Secondary Steelmaking process/plant.

In the Electric Arc Furnace (EAF) Route, DRI and scrap metal are used as raw material inputs for this process. The material inputs (charge) are melted by transmitting huge quantities of electrical energy through electrodes into the charge. Oxygen is also blown into the charge to assist with the release of carbon and other impurities. The molten steel is tapped into a ladle and taken to the Secondary Steelmaking process. For more information on the working of the EAF process the reader is referred to [22].

During the Secondary Steelmaking process argon is injected as a means of stirring the molten steel. Alloys are added, degassing performed and sometimes powder reagents are injected as required. From this stage of processing the molten steel, with the desired steel grade and temperature, is taken to the continuous caster.

During the continuous casting process molten steel is poured into a tundish, that acts as a reservoir, at the top of the machine. It is fed through a water cooled mould and sprayed with water to produce a continuous slab, billet or bloom depending on the mould size and its shape. The slabs, billets or blooms are transported to the hot rolling mill for further processing. For more information on continuous casting the reader is referred to [23].

Steel products can be classified according to shape, such as flat products and long/structural products. Slabs are used to roll flat products such as steel plate or strip, while blooms and billets are used to roll long products such as beams.

Semi-finished products are first reheated in a reheating furnace to about 1200°C. These products are then fed to the applicable roughing mill where the initial reduction is performed until the shape and dimension approaches values that can be handled by the finishing mill. Plate mills and strip mills handle slabs. Blooms and billets are handled by long product mills.

The processing of plates in a plate mill consists of turning the plate 90° after some passes and effectively rolling the plate in the length and the width. Plate is perhaps 10 to 20mm thick and up to 3 meters wide.

Strip, produced from slab, is further processed by a finishing mill until the desired reduction and dimension are achieved for the strip. The long strip is cooled on a run-out table with water curtain sprays installed in order to ensure that the right coiling temperature is achieved, which will guarantee the required mechanical properties. The cooled down strip is then coiled or cut up in sheets.

An alternative finishing strategy is the so-called Steckel mill (see figure 2.2), which is the focus of this investigation and will be described in more detail in the following sections.

If necessary, the coiled product can be treated further by means of cold rolling to improve surface quality and of course to produce a thinner product.

A roughing mill also handles the initial stage of processing of blooms and billets. After the roughing stand, the piece of steel passes through a succession of finishing stands that change its size and shape. In a universal mill, all sides of the product are rolled at the same time, whilst in other mills only two sides are rolled at a time, and the product has to be turned over to allow rolling on the other sides.

Long products are produced in a vast number of shapes and sizes. They can have cross-sections shaped like a H, I, U, T, squares, rectangles, circles, hexagons, angles and rails.

Forms of further processing that hot rolled products may undergo before they are finally used to make an end product include the following:

- Fabricating: Steel sections are cut, welded and otherwise prepared to form the steel frame of a building.
- Coating: Corrosion preventative coatings are applied to the steel surface.
- Cold rolling and drawing: Changes thickness and surface quality.
- Profiling: Sheet pressed into the correct shape for specific applications.

2.3 Hot Rolling Process Flow

A typical reversing hot rolling process with a Steckel mill as the finishing mill consists of the following units, as can be seen in figure 2.1 [21, 4, 1]:

- Slab reheat furnace: After the continuous casting of the slabs they are stored until the hot rolling mill process is ready for further working of the slab. These slabs are reheated to a

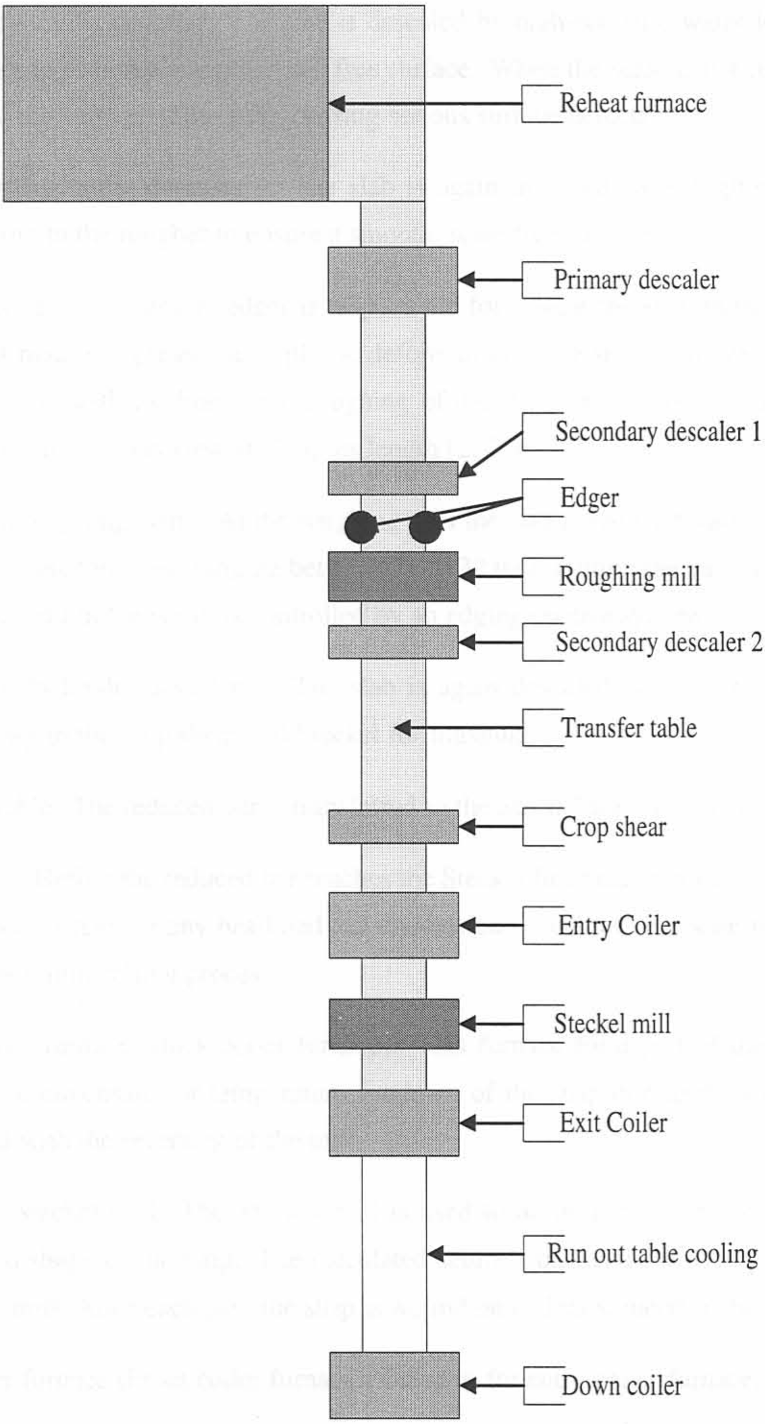

Figure 2.1: Hot rolling process flow.

temperature in excess of 1200°C. The slab is discharged from the reheat furnace at a pre-set discharge temperature, as calculated by the setup program. The temperature is measured and a recalculation of the Rougher setpoints is performed to ensure that the material can be rolled.

- Primary hydraulic descaler: The slab is descaled by high-pressure water jets before going to the rougher to ensure a smooth, scale free surface. When the scale is not removed the scale is rolled into the surface of the strip, causing serious surface defects.

- Secondary hydraulic descaler 1: The slab is again descaled, with high-pressure water jets, before going to the rougher to ensure a smooth, scale free surface.

- Vertical edger: The vertical edger is responsible for rolling the strip in the width to limit the amount of material spread due to plastic deformation of the strip. This vertical edging is done in conjunction with the horizontal roughing of the strip. The resulting strip has a dog-bone shape, when the strip is viewed along its length [2, 24].

- Horizontal roughing stand: At the roughing mill the slab is reduced through a set of passes to an intermediate thickness ranging between 22 to 32 mm. During the passes at the Rougher, the material spread in the width is controlled by an edging control system.

- Secondary hydraulic descaler 2: The slab is again descaled, with high-pressure water jets, before going to the crop shear and Steckel for finishing.

- Transfer table: The reduced bar is transferred to the Steckel finishing stand on this table.

- Crop shear: Before the reduced bar reaches the Steckel finishing stand the head- and tail pieces are cropped to remove any head and tail end- defects, such as crocodile teeth[1] [2], caused by the roughing mill rolling process.

- Entry coiler furnace (Back coiler furnace): This furnace form part of the finishing mill and is used to compensate for temperature rundown of the strip due to the longer process times associated with the reversing of the mill.

- Finishing Steckel mill: The Steckel mill is used to accurately control the centerline gauge, profile and shape of the strip. The calculated setup is changed for each pass before the strip enters the mill. After each pass the strip is wound on coilers situated in the coiler furnaces.

- Exit coiler furnace (Front coiler furnace): Same as for entry coiler furnace.

- Run-out table cooling: When the strip completes its passes on the Steckel mill and is on final gauge, the strip is cooled by water curtains on the run-out to table fix the microstructure of the metal and thus its mechanical properties [25, 5].

- Down coiler: After the completion of the previous steps, the strip is coiled on the downcoiler for packaging or to be cut up into plates at the dividing shear.

Before a slab can be rolled, certain critical control setpoints are calculated. The setpoint calculation determines rolling parameters such as [21]:

- Reheat furnace discharge temperature;
- Number of odd passes to be completed by the roughing mill;
- Number of odd passes to be completed by the Steckel mill;
- The reduction taken at each pass for both the roughing and Steckel mill;
- The magnitude of edging for each pass on the roughing mill;
- Shape control settings for each pass on the finishing Steckel mill;
- Descaling practice for each pass on the Steckel mill;
- Run-out table cooling settings, e.g. run-out table speed and water cooling spray patterns;
- Downcoiling temperature of the strip.

The setup and control strategy selection falls into Level 2[2] of the automation control system architecture [1]. There are two main approaches that exist for setpoint calculation [21, 6, 26]:

- The first is based on experimental data gathered from rolling test slabs from which fixed setpoints for each material type, width-group and aimed gauge are calculated. These rolling schedules are stored in tables and referenced when the mill is setup for a slab. This approach does not allow for process variations and does not yield very good quality steel. This type of scheduling is not used much in modern times.
- The second approach is based on mathematical models that simulate the interaction between the material and the mill [1]. Using an optimization search criteria, the optimal solution, the rolling setup, is found by solving a static optimization problem. The employed models used in this optimization problem are adapted on a long time scale and after each pass the setup schedule is updated during the completion of the rolling schedule as soon as plant measurements become available. The long term adaption of the process models is termed bar-to-bar adaption and the updating of the rolling schedule is termed in-bar adaption.

[1]This is encountered when the head or tail end splits open like a gaping mouth of a crocodile.

[2]In [1] the control system architecture is explained for the rolling mill environment. Level 1 is the dynamic control level accounting for dynamic control. Level 2 is termed as the supervisory control level. Level 3 is termed as the plant wide control level. Level 2 is responsible for mill setup, slab routing, fault diagnosis, maintenance management, direct tracking and analysis, alarm management, statistical process control and data analysis. Level 3 is responsible for dynamic scheduling, order book management and batch tracking.

The Steckel mill pass schedule calculation is an iterative steady state optimization problem that finds an optimal or suboptimal solution for the various criteria [1, 21]:

- The minimum number of odd passes;
- The correct shape at final gauge;
- Rolling forces and rolling torque that are within the mill designed specification;
- The correct profile at 9 mm thickness[3];
- Work roll bending requirements that are within the control range;
- Run out table cooling and mill speeds that will ensure the correct downcoiling temperature for the required mechanical properties of the material.

Before each pass a recalculation of the Steckel mill setpoints are done and the setpoints are updated (in-bar adaption). The procedure normally followed is:

- Setting the roll gap using the Automatic Gauge Control (AGC) System;
- Shifting the work rolls laterally for a predefined distance to minimize work roll wear (20 mm each time);
- Apply pre-bending to the work rolls for profile and shape control;
- Squaring the strip to the center line of the mill using side guides;
- For each pass the strip is passed through the roll gap and wound in the opposite coiler furnace, where the strip is annealed while the pass is completed;
- During rolling the bending of the work rolls is dynamically controlled to ensure the correct shape and profile of the strip. Whilst the strip is thicker than 9 mm, profile control is performed, and below this gauge shape control is done. The profile of the strip is typically measured using a scanning X-Ray thickness measurement device. The movement of the strip and the fixed position of the scanning X-Ray give a zig-zag reading of the strip crown. The shape and flatness is measured after the completion of the rolling passes by a surface inspection system that can for example use neural network technology and intelligent image processing algorithms to identify shape/flatness defects such as quarter buckle [1].
- The Automatic Gauge Controller (AGC) controls the roll gap to ensure a constant centerline thickness along the length of the strip;

[3] It is generally regarded that below 9mm of thickness, little control can be exerted in order to control the strip profile. The strip shape and flatness are controlled during the later passes when the strip thickness is less than 9mm.

- The BISRA-Davy gauge-meter compensator predicts the stretch in the mill housing [27, 1] due to the rolling forces and adds a trim to the setpoint of the roll gap setting. In order to compensate for the stretch the roll gap setting is manipulated in order to achieve the required draft. This compensator employs a positive force feedback strategy in order to regulate the output gauge.

Because the strip thickness is measured some distance from the mill bite, a normal closed loop control strategy will either be too slow or unstable due to transport time (t_d). To combat this phenomenon a Smith predictor is normally employed in the feedback loop to compensate for the transport delay [20].

2.4 Steckel Finishing Mill

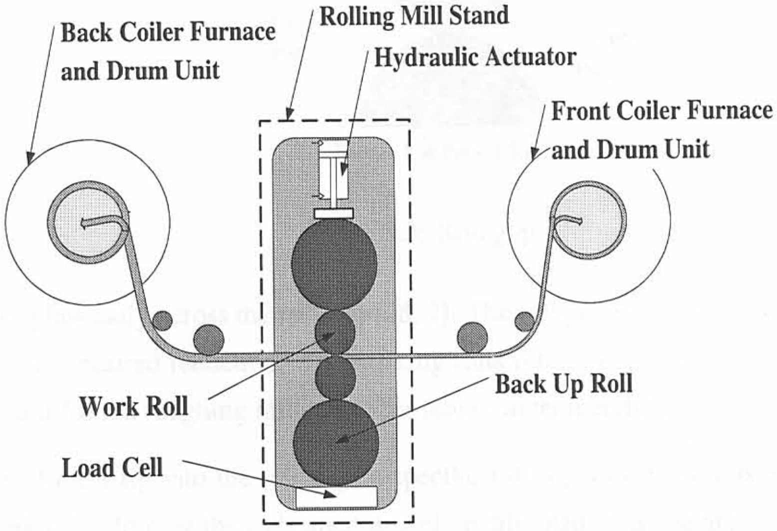

Figure 2.2: Steckel Hot Rolling Mill.

Rolling is the process of shaping metal by passing it between rolls revolving at the same peripheral speed and in opposite directions. The Steckel mill (see figure 2.2) is usually a single stand, four high, reversing mill consisting of two work rolls and two back up rolls. The mill employs multiple passes to achieve the desired final thickness reduction of the strip. The reversing of the strip during the multiple passes results in a temperature rundown of the strip. This temperature reduction makes it more difficult to to work the strip as the rolling forces increase. The temperature rundown is compensated for by winding the strip on coiler drums situated in coiler furnaces regulated at a temperature of $970°C$.

Massflow holds across the roll gap [2, 28] (see figure 2.3), and with negligible metal spreading in the width of the strip, it is found that:

$$v_1 h_1 = v_2 h_2 \tag{2.1}$$

v_1: strip's entrance velocity into the roll gap

h_1: strip's entrance thickness into the roll gap

v_2: strip's exit velocity from the roll gap

h_2: strip's exit thickness from the roll gap

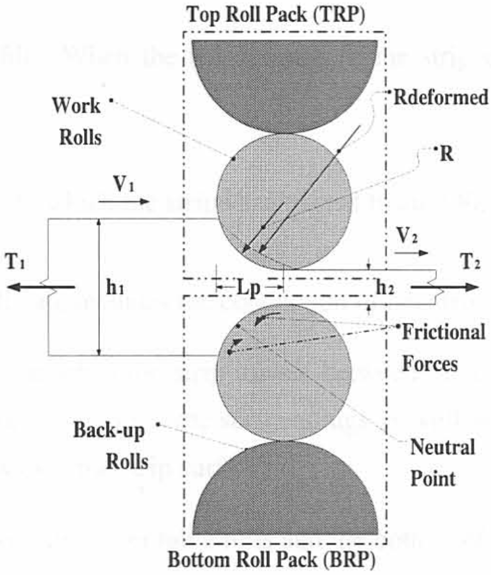

Figure 2.3: Roll gap.

The metal flows plastically across the roll gap [28, 2]. The roll gap is set at a gap setting calculated in order to achieve the desired reduction. The working rolls rotate at a speed, v_{roll}, and the strip enters the finishing stand from a roughing mill, on roller tables, at temperatures in excess of $1000°C$.

Upon entrance of the strip into the roll gap, a specific roll separating force is exerted by the metal strip on the work rolls, forcing the rolls apart and elastically flattening the arc of contact. The rolling mill frame has a finite stiffness and stretches due to this forcing phenomenon. This stretch affects h_2 adversely. The working rolls furthermore bend elastically over the width of the strip [7, 10]. This elastic deformation is due to the separating force that pushes the working rolls further apart. The uncontrolled elastic bending of the rolls is greater in the mill center. The plastic behavior of the metal in the roll gap assures that the metal fills the whole gap, thus due to the bending of the rolls the strip is thicker at its center. This thickness deviation of the strip over the width is defined as crown.

Factors that influence the strip crown and shape are [29]:

- Initial roll camber: The rollers can have a natural positive or negative camber (crown). In this dissertation it is assumed that the natural camber is zero.
- Roll thermal camber: The temperature build-up on the rollers creates thermal expansions of the roller diameters (especially the work rolls).
- Roll deflection: The elastic bending of the rollers falls into this category.

- Roll wear: The rolling campaign determines how much the rolls deteriorate with time due to wear. Rolls are typically changed after the rolling of 16000 km strip.

- Material structure: If the material is hard the roller wear is greater and the roller deflection is also significant.

- Strip temperature profile: When the temperature of the strip declines it becomes harder to deform the strip.

The elements of heat transfer to which the strip is subjected to are [30, 25]:

- Heat transfer in the roll gap, includes the conduction of heat from the strip to the working rolls.

- Radiation and convection when the strip travels between the coiler furnaces account for the heat that is radiated from the strip to the surroundings as well as the convection cooling of the strip due to the air flow over the strip surfaces.

- Heat conduction between the roller table rolls and the bottom of the strip.

- The descaling sprays situated between the coiler furnaces and the finishing rolling stand cool down the strip, by spraying the strip with water at a temperature of typically 35°C.

- The sheet is reheated in the coiler furnaces to compensate for heat loss during the completion of the pass.

Temperature of the strip as a function of time and position in the mill is of great importance because the temperature of the strip influences the material yield stress and in effect the rolling loads. The thermal crown on the working rolls increases with strip temperature and the amount of plastic working in the roll gap [10], and influences the output thickness crown of the strip. Heat transfer during rolling is investigated in [30] and only an introduction to the heat transfer problem is given in this dissertation, as modelling of heat transfer phenomena falls outside the scope of this work.

Slipping occurs between the work rolls and the strip along the arc of contact, and thus the strip speed is only equal to the work roll speed at the neutral point (see figure 3.2). The velocities, v_1 and v_2, are respectively slower and faster than the roll speed. This results in friction forces acting along the arc of contact that pull the strip into the roll gap. At the exit of the roll gap the friction forces are reversed and oppose the delivery of the strip from the roll gap [2]. The net effect of these friction forces is the creation of a friction hill [28, 2, 24].

The position of the neutral point can be shifted by applying tension to the strip between the down coiler and the roll gap (back tension, T_2) as well as between the up coiler and the roll gap (front tension, T_1). If back tension is applied the neutral point moves towards the entrance of the roll gap and with the application of front tension the neutral point is shifted towards the exit of the roll gap.

The application of tension to the strip reduces the rolling load by means of reducing the friction force components. The application of back tension is more effective in reducing the friction force component of the rolling load than the application of front tension [2].

The working rolls also deform elastically along their axis and over the width of the sheet [2]. This elastic deformation is due to the separating force that pushes the working rolls further apart. The elastic deformation of the rolls is greater in the center of the sheet, due to the fixed end positions of the roll neck of the rolls. This elastic deformation of the work rolls has the effect to make the sheet thicker in the center than at the edges, thus giving the sheet a positive crown[4].

2.5 Conclusion

In this chapter a brief discussion was given on where the hot rolling process fits into the steelmaking process. The practical operation of a hot rolling process was described and discussed, and the elements of the hot rolling process were identified and described. The Steckel finishing hot rolling mill is the focuses of this dissertation, and in this chapter this finishing mill was defined and discussed. Lastly the general process behaviour of the Steckel rolling mill was discussed.

In the following chapter the nonlinear models necessary to simulate the centerline thickness and tension in the sheet whilst rolling are identified. These models are developed mathematically and further process behaviour is discussed during the model derivations.

[4]In the Appendix rolling definitions are given.