Status, achievements and outlooks of endless steel strip production with a focus on electric steels

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Abstract
Arvedi ESP (Endless Strip Production) technology has been proved a breakthrough rolling technology in terms of its distinctive advantages in hot rolled steel strip production. The status, achievement and potential of high quality electric steels production through Arvedi ESP technology are addressed in this paper with taking the trend, basic requirements and factors which influence quality of the Si-steel into account. It can be concluded that Si-steel production through Arvedi ESP process has clear advantages in comparison to the conventional routes, especially for thinner and higher quality grades.

1 Arvedi ESP ─ the most advanced TSCR technology

Producing high quality steel products with lower cost, lower energy consumption, shorter production routes and better environmentally friendly operation is the trend for steelmakers. For hot strip production, this trend is well addressed by the continuous evolution of Thin Slab Casting and Rolling technology (TSCR, see Figure 1) where the casting and rolling part are connected together for direct hot strip production [1].

As the latest and most advanced TSCR technology, the Arvedi ESP process meets best the general trend and also requirement for all steelmaking industries, lower cost, lower energy consumption, shorter production routes and better environmentally friendly operation. A schematic illustration of the ESP layout is shown in (Figure 2), being composed of four main plant sections in addition to infrastructural and auxiliary facilities. The first section consists of a thin-slab caster featuring liquid core reduction followed by rolling in linked high reduction mills positioned at the exit of the continuous caster. In the second section, the temperature of the intermediate transfer bar is heated by an induction heater according to finishing rolling requirements. The third section, comprising a finishing mill and a cooling line, is designed to allow the strip to be rolled to thicknesses between 0.8 mm and 12.7 mm at maximum strip width. The fourth section consists of a high-speed shear and downcoilers. Advanced automation systems ensure that all production and product quality parameters are satisfied [2][3].

Figure 1. The evolution of the TSCR technology. The principal elements of the plant are defined as follows: C – cooling/coiling; CF – Cremona – furnace; F – finishing mill; IH – inductive heater; IT – intermediate treatment (heated transfer table or cooling); R – roughing mill; T – tunnel furnace.
Arvedi ESP (Endless Strip Production) is believed a breakthrough rolling technology for the whole steelmaking world since its commissioning (by Primetals Technologies, former Siemens VAI) in 2009, this being proven true by the running of 4 Arvedi ESP production lines, 1 in Cremona, and 3 others later installed by Primetals Technologies at Rizhao Steel Co./China. Due to successful operation and huge benefits resulting from ESP production, Rizhao Steel Co. further ordered additional 2 ESP lines which will be in service soon.

![Figure 2. Schematic illustration of the ESP layout.](image)

High quality electrical steel — increasing demand, thinner gauge and more homogeneous property

Si electrical steel, generally divided into grain oriented (GO) and non-grain oriented (NGO) types, is an iron alloy containing significant amounts of silicon and is tailored to feature certain magnetic properties. The major types of Si-steel regarding to their Si contents, gauge and production routes (hot rolled and cold rolled) are listed in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Si content, wt.%</th>
<th>Gauge, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot Rolled (NGO)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Si steel</td>
<td>1.0~2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>High Si steel</td>
<td>3.0~4.5</td>
<td>0.35 &amp; 0.5</td>
</tr>
<tr>
<td>Cold Rolled NGO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low carbon electrical steel</td>
<td>&lt;=0.5</td>
<td>0.50 &amp; 0.65</td>
</tr>
<tr>
<td>Si steel</td>
<td>0.5~3.2</td>
<td>0.35 &amp; 0.50</td>
</tr>
<tr>
<td>Cold Rolled GO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Common GO-Si-steel</td>
<td>2.9~3.3</td>
<td>0.20, 0.23, 0.27</td>
</tr>
<tr>
<td>HiB GO-Si-steel</td>
<td>2.9~3.3</td>
<td>0.30 &amp; 0.35</td>
</tr>
</tbody>
</table>

Being widely used for electric motors, generators, transformers, reactors and the like in domestic electrical appliance and electric industry, up to now no alternative material is capable of replacing electrical steel in this range of use. As a result, the demand for high quality electric steel is constantly increasing since their invention.

Electrical steel must satisfy several requirements. Their priorities depend on the specific application such as high magnetic permeability, low hysteresis losses, anisotropy of losses as well as ease of cutting laminations to shape. Low core loss (power loss caused by magnetization via alternating current excitation at a particular operating frequency and a particular maximum flux density) is the principal quantity of interest for soft magnetic materials.
The increasing demands of Si-steel lead to increasing requirements not only for magnetic properties but also for e.g., mechanical properties, geometrical properties and surface quality as they influence their processing and application in a decisive manner. Various requirements for electrical steel are summarized in Figure 3.

**Geometrical properties**
- width, thickness, profile,
  - crown

**Mechanical properties**
- yield/tensile strength,
- hardness, elongation,
- ductility

**Material properties**
- chem. analyse, isolation,
  - stacking behaviour

**Magnetic properties**
- hysteresis losses,
- polarisation, permeability

Figure 3. Requirements for Si-Steel Strip product to be delivered to die-cutting

These properties determine both, chemical composition and processing routes including steel making, casting, heating, hot rolling, cold rolling, annealing and applying electrically insulating coatings. A standard production route for GO and NGO Si-steels is schematically illustrated in Figure 4. It is important that each single step can affect the final product properties. For example, according to experience, the sensitivity ratio of the three main steps — steelmaking, hot rolling and cold rolling — to the final magnetic properties is about 4:4:2. Therefore it is clear that production via the TSCR process influences the final properties of both, hot rolled and cold rolled Si-steel.

Figure 4. Standard production routes for NGO + GO silicon steel
High quality Si-steel fabrication via Arvedi ESP process

Marking the latest development in TSCR technology, there is no doubt that common practise upstream processes (from blast furnace to hot rolling) with the target of thin gauges and uniform final product properties can best be fulfilled via the Arvedi ESP route for a variety of steel grades. The special characteristics of Arvedi ESP process shows distinctive advantages over other conventional and TSCR technologies, proven by a wide range of steel grades produced on a daily basis in the various ESP lines installed, ranging from ultra-low carbon to high carbon steels with broad applications including HSLA, multiphase and TRIP as well as silicon steel (up to 3%), AHSS and stainless steels. For Si steels, the advantages of ESP technology are even more pronounced compared to conventional steel grades production. Production of hot rolled NGO Si grades has successfully been tested in Cremona [4] and concepts of producing GO Si-grades using the ESP route have also been presented recently [1].

Below, the advantage and potential of high quality electric steels production through Arvedi ESP technology are addressed, taking the requirements and parameters which influence the quality of Si-steel into account.

**Higher cleanliness beneficial to magnetic properties**

It is well known that high cleanliness is required for high quality steels. For Si-steels it is essential to keep the impurity content as low as possible in order to improve magnetic properties. Impurities do not only impede movements of magnetic domains and increase coercivity, they also induce closed magnetic domains which deteriorate ease of magnetization. Therefore, steel cleanliness is an important ingredient for the reduction of the magneto static energy and hysteresis losses of the final product. Impurities are also known as being detrimental for grain growth and proper texture development in view of beneficial to magnetic properties [5].

Besides the treatment in secondary metallurgy and the efficiency of re-oxidation prevention, casting operation and control also play a critical role for steel cleanliness as entrapment of ladle slag, refractories and mould slag as well as clogging and the agglomeration of inclusions at the steel/mould flux interface have an adverse influence on steel cleanliness. The funnel-shaped mould with a thickness of 90 – 110 mm is one feature of the Arvedi ESP process which ensures a stable mold condition and a low breakout rate as well as beneficial conditions for macroscopic steel cleanliness. In addition, features such as intensive mould cooling (providing the possibility of internal heat transfer of up to 4 MW/m²), the design of the strand guiding system, secondary cooling together with liquid core reduction and the low solidification time of less than 2 minutes result in favourable conditions for less pronounced centre segregations compared to conventional slab casting. The resulting higher temperature gradients in the solidifying layer and subsequent higher post solidification rate guaranty homogeneous primary and secondary microstructure in front of high reduction mill. The combination of proper treatment in the steel plant and the special design of the Arvedi ESP casting process assure stable production of Si grades, a cleaner steel compared to conventional routes and, thus, improved magnetic properties of the Si-steel.

**High machinability due to homogeneous mechanical properties**

High machinability is one of the critical requirements of premium quality Si-steel. For example, the magnetic circuit of motors and transformers consists of a number of stapled sheets that are pre-manufactured with the help of high-speed stamping, reaching a speed of up to 1000 beats per minute. Inhomogeneities in the mechanical properties of the strip and/or existing defects can lead to equipment failure during stamping, downtime and reduced productivity. In the Arvedi ESP process, homogeneous mechanical properties of the strip are guaranteed through the following characteristics:

(1) The ESP casting process assures a favourable condition for beneficial macroscopic steel cleanliness as well as less centre segregations of the slab compared to conventional slab casting. This is an important prerequisite for a homogeneous formation of microstructure in the final product and also for the prevention of the formation of large primary nitrides or other undesired precipitates.

(2) The two-step rolling concept of the Arvedi ESP provides decisive advantages for precise control of the microstructure in the final product, thus homogeneous mechanical properties. The high reduction mills, directly placed behind the caster exit work on slabs coming from the caster having an inverse temperature profile, i.e. a soft and hotter core compared to the surface (depending on the casting parameters the temperature difference may be up to 300°C). This makes very high reductions (up to more than 50% for each pass) possible. Because of shear effects this results in more effective deformation in the centre of the slab in comparison to working on a slab with a temperature profile after conventional reheating or tunnel
furnace. This homogenized through thickness deformation accounts for good recrystallization conditions also at the centre of the strand, ensuring a homogenous recrystallized microstructure for the deformed slab at the exit of the high reduction mill and before entering the Finishing Mill after induction heating [6][7]. This outstanding feature of the 2 step rolling concept in combination with the inductive heater results in highly homogeneous grain structures in through thickness direction.

(3) Unlike other conventional TSCR process, there is no processing deviation caused by threading and tail speed-up involved in the Arvedi ESP process. Constant casting and rolling speeds along large parts of a sequence result in extremely stable rolling conditions via real endless production mode. For example, as demonstrated for the FM exit temperature, the real time chart shows a standard deviation of 2°C for a production period of more than 2.5 hours with strip thicknesses between 1.0 mm and 1.3 mm. This in turn results in coils that possess homogeneous properties within very tight tolerances all along the entire strip as the strip is divided into coil portions right in front of the down coilers using a high speed shear.

Big process window and higher flexibility of ESP process for production of NGO and GO Silicon steels

ESP process is very flexible process. The production of NGO and GO steel grades needs different temperature during hot rolling. This is due to the fact that from the technological point of view, the precipitation of nitrides or sulphides are is desired during hot rolling or not. The another issue is the creation of condition for formation of GOSS texture in the finishing for GO steels. ESP has some possibilities to set up necessary thermo-mechanical schedules required by technology. This includes speed variations, set up slab temperature before HRM, using of ENCO-panels after HRM and induction heating.

Superior strip geometrical characteristics and flatness

For Si-steel, a flat and clean surface is necessary to reduce the number of free magnetic poles, hence, to reduce magnetostatic energy and resistance for magnetic domain movement and therefore reducing magnetic hysteresis losses and coercivity. In addition, the magnetic performance of Si grades in the final product is strongly influenced by the stacking accuracy of the final die-cut material, which is defined by the profile and flatness of the as-delivered Si-Steel strip. In this aspect, ESP produced steel strip has distinctive advantages.

The pre-rolling of the thin slab immediately after solidification in the continuous caster allows precise gauge and profile control and results in a transfer slab with very precise and reliable geometrical characteristics. The translational invariance of the real endless production mode (no processing deviation caused by threading and tail speed-up) ensures a constant gauge along the whole coil length and high precision of the cross-section (Figure 5), stable flatness and transverse crown including head and tail of coils.

![Figure 5. ESP hot rolled low carbon steel strip processing constant gauge along the whole coil length and high precision of the cross-section.](image-url)
ESP product gauge tolerances are shown in Figure 6 together with other European reference standards. The results show that the Arvedi ESP hot rolled coil tolerance is well within the cold rolled automotive standard.

![Figure 6](image)

Figure 6. Arvedi ESP hot rolled coil tolerance is well within the cold rolled automotive standard.

The surface roughness of ESP products has a mean value less than 1.5 µm, which is comparable with average roughnesses after conventional production and cold rolling. As an example, the topography of a 1.80 mm thick HSLA sample (Figure 7) was investigated by using the Infinitive Focus method, which revealed an average roughness of 1.36 µm.

![Figure 7](image)

Figure 7. 3-d surface topography of ESP material revealed a mean surface roughness of 1.36 µm using the Infinitive Focus method.

**Optimization of the downstream process by ultrathin gauge**

The market for Si-Steel is in the area of 0.2 to 1 mm in thickness for final application (see Table 2). The thickness of hot-rolled Si-steel sheet in the traditional process is normally in the range of 2.0-2.5 mm. Producing ultrathin hot rolled strips is quite difficult via conventional processes due to the operational challenges caused by threading as well as the peculiarities of the Si-steel production process such as high rolling forces. Therefore, to obtain desired final thicknesses in the range displayed above a further thickness reduction through cold rolling is necessary. As material with high amounts of silicon exhibits pronounced work hardening and behaves very hard and brittle in general, the maximum cold reduction is normally limited to 70% in industrial production because of rolling-force capacity limits, strip profile requirements as well as the risk of strip breaking. This is also the case when cold rolling is combined with intermediate annealing for softening.
Producing via major technological routes for production of grain-oriented electrical steel, as shown in Figure 8, two steps of cold rolling combined with an intermediate annealing has to be done, to obtain a strip of 0.3 mm thickness if a hot strip produced via conventional or batch type TSCR is used [1].

Compared to the traditional process, the endless rolling mode on the ESP unit allows to obtain a strip with a thickness of 0.8 mm without reducing overall performance. Concerning thin Si-steel production, hot-rolled sheet with a thickness of 0.8-1.2 mm also makes it possible to produce transformer steel with thickness up to 0.23 mm, using the technology of single-stage cold rolling without intermediate annealing.

More recently, driven by the rapid development of electro mobility, electric steel strip tends to be produced with thinner gauge and higher required magnetic properties for final application. This is a big problem if conventional TSCR produced strip of 2~2.5 mm thickness is used. For example, to produce a final 0.1 mm thickness strip, the current two step cold rolling combined with annealing process cannot fulfil this task, even when using higher cold reduction of around 75% already having considerable risk of strip breaking. In this case, it is necessary to apply more steps of cold rolling combined with annealing (e.g. 3 cold rolling + 2 annealing cycles). However, with ultrathin ESP produced strip, this problem can be avoided by using current technology. Thus, to meet the electric steel market trend for even thinner and higher specified magnetic properties, ultrathin hot Si-steel strip production through Arvedi ESP process seems to be the only choice.

Improved surface quality by minimizing surface defects
The newly developed Arvedi ESP process has many advantages regarding improvement of surface qualities by its specific process design compared with other conventional rolling processes. Certain surface defects which may frequently occur in a conventional rolling process, e.g. scratches (particularly strip head and tail), can be avoided or reduced in great content due to its specific design. Minimizing certain defects critical for high quality Si-steel production are briefly described below based the specific characteristics of ESP process.

1 Surface cracking and edge cracks
Surface cracking is one critical issue for the production of GO electrical steel via the conventional process route, where reheating the slab to a temperature higher than 1350°C necessary to dissolve the precipitates in question. This leads to severe scale melting in the furnace and brings up corresponding operating and maintenance issues in the affected area. At the same time, strong grain growth and oxide penetration at grain boundaries (especially for the high Si content steel grades) may lead to surface cracking in later processing steps [2][7]. The higher reheating temperature may also cause burnt edge defects, which can further lead to edge cracks or even strip breaks in the hot rolling process. [8].

In the Arvedi ESP process, this problem is avoided, because the directly linked caster allows exit temperatures above 1000 to 1100°C and is thus able to avoid the precipitation of sulphides and nitrides.
before hot rolling. Especially, the high core temperatures in the range of 1200 to 1350°C are important for the production of electrical steel grades in this regard.

Unlike other processes with a long furnace for reheating in front of the roughing mill, the ESP process uses an induction heating system to adjust the temperature of the transfer bar after high reduction. During a very short time the slab temperature is increased up to 1200°C, depending on the final target thickness for further finish rolling after descaling. The low average processing temperature compared to conventional and TSCR rolling with tunnel furnace strongly decreases scale growth and the occurrence of defects caused by conventional reheating, like burnt edge, crazing, red scale and the like are ruled out by design.

2 Edge crack
Edge cracks occurring during hot rolling provides another challenge for Si-steel. There are many reasons for edge crack defects formation on hot rolled steel strips. Edge cracks due to burnt edges can be avoided via ESP process; in addition, edge crack defects caused by several other reasons can be relieved via ESP process, such as cracks induced by strip heads bouncing along the run-out table (ROT) as well as contact of strip edges with side guides during threading periods where no strip tension between finishing train and coiler can be applied. Another issue are inappropriate edge temperatures during deformation which can well be controlled by edge heating. As lateral motions of the strip during endless processing are virtually non-existing very accurate edge heating can be applied if needed.

3 Work roll damage caused defects
Work roll (WR) damage is responsible for many surface defects. These defects show different shapes and severity depending on the damage level of the work roll. Despite the unavoidable WR wear with increasing rolling length, there are two critical factors directly related with WR damage: work roll thermal fatigue and impaction on WR due to threading. In conventional hot rolling lines, these two factors cannot be avoided by design due to its batch rolling process. However, in ESP process, because of threading at all and stable (constant) rolling conditions as a whole, work roll damage is significantly reduced. This is directly reflected by the enhanced surface quality of ESP strips.

Summary
Combining trends in demand for electrical steel with the technological requirements and factors that influence the final product quality of Si-steel grades, the production of electrical steels via Arvedi ESP technology has been addressed. In comparison to conventional TSCR process, the Arvedi ESP process has distinctive advantages not only with respect to improvement of magnetic properties but also regarding the optimization of downstream processing of Si-steel. Especially, ultrathin hot Si-steel strip production via the Arvedi ESP process seems to bear significant optimization potential to meet the electric steel market trend pointing towards even thinner gauges and grades with further improved magnetic properties.

References
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