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Recycling of Steel

Bo Björkman, Caisa Samuelsson

MiMeR — Minerals and Metallurgical Research Laboratory, Luleå University of Technology,
Luleå, Sweden

6.1 INTRODUCTION

Recycling of steel is a very old business, and it should be pointed out that in most developed
parts of the world we have a very well-developed system of scrap collectors, scrap-
processing companies and steel plants utilizing the scrap. For the scrap-treating companies
and the steel plants, steel scrap is a very valuable resource. From the scrap that is collected,
losses occur to residues in the scrap processing and in material streams that are recycled in
other metal cycles, e.g. iron units present in scrap sorted as scrap for copper making.

Steel scrap in steelmaking is usually recycled to either an electric arc furnace (EAF), in what
usually is labeled scrap-based steelmaking, or to the basic oxygen furnace (BOF), in
ore-based steelmaking, where there exists a considerable need for cooling to avoid too high
temperatures as a result of exothermic reactions. It should be pointed out that in the steel pro-
duced in ore-based steelmaking, about 10–20% is from scrap used for cooling in the BOF.
The world production of steel was 1547 Mt in 2012 (World Steel Association, 2013), a record high
production. Of these 29.3% was produced in the EAF process. Almost all of the steel produc-
tion based solely on scrap is produced in the EAF process. Assuming then 100% of scrap use
in an EAF and about 15% of the steel produced in ore-based steelmaking originating from scrap
used as coolant gives about 40% of steel production in the world based on scrap. Some references
indicate a lower value, thus indicating that in developing countries ore is more often used as
coolant in BOF steelmaking than scrap. The share of steel produced from scrap in Western Europe
in 2012 was about 50–55%, calculated based on the same assumptions (Eurofer, 2013). This
figure is in good agreement with statistics on the scrap consumption in Western Europe, indic-
ating about 55% of steel production is based on scrap.

In addition to much lower emissions to the environment in general, steel production in an
EAF process based on scrap contributes much less to the emission of CO₂ and has a much
lower total energy consumption. The focus in recent years has been on research toward
decreased emissions of greenhouse gases from steelmaking in among others the European
ULCOS project (ULCOS, 2013), and in this context a comprehensive evaluation of CO₂
emissions and energy consumption in benchmark BOF steelmaking and EAF steelmaking as well as for different alternative processing routes has been presented. The benchmark emissions of CO₂ from the BOF route and the EAF route are about 1770 and 380 kg CO₂ per ton liquid steel, respectively, and the benchmark total energy consumption is about 4900 and 1100 kWh, respectively, per ton of liquid steel (e.g. Birat et al., 2004).

Figure 6.1 illustrates the increase in world steel production by region in recent years, showing a drastic increase in steel consumption, mainly driven by economic development in China. China’s steel production has increased from 182 Mt in 2002 to 716 Mt in 2012. About 46% of today’s world production of crude steel is produced in China. It is important when considering the share of steel produced from scrap that as long as the world consumption of steel increases in the way illustrated in Figure 6.1, and as a majority of the steel is in final products that have a quite long life time, a considerable amount of the steel produced has to come from ore-based steel production, despite the high recycling rate of collected scrap, cf. Table 6.1.

Figure 6.2 illustrates the use of steel split into different product groups. The by far largest use of steel is in construction, an application which

<table>
<thead>
<tr>
<th>Application Area</th>
<th>Estimate for 2007 (%)</th>
<th>Target for 2050 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td>85</td>
<td>90</td>
</tr>
<tr>
<td>Automotive</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td>Machinery</td>
<td>90</td>
<td>95</td>
</tr>
<tr>
<td>Appliances</td>
<td>50</td>
<td>75</td>
</tr>
<tr>
<td>Containers</td>
<td>69</td>
<td>75</td>
</tr>
<tr>
<td>Total</td>
<td>83</td>
<td>90</td>
</tr>
</tbody>
</table>

From World Steel Association (2013).
has a very long time in use, cf. Table 6.2, but most of the steel applications have a quite long time in use.

Steel stocks in use have reached saturation in several developed countries and are not increasing anymore, even declining in some countries, whereas some developed countries and most of the rest of the world still have increasing stocks of steel in use. The saturation level for steel stock in use is at $13 \pm 2$ t/capita (Pauliuk et al., 2013). In China, the country that showed the fastest-growing steel consumption so far in this twenty-first century, consumption are expected to peak between 2015 and 2020 (Pauliuk et al., 2012). As a saturation of steel stocks in use occurs, the fraction of steel production based on scrap can and will increase. In 2050, the share of steel produced from scrap has been estimated as about 80% (Pauliuk et al., 2012). Other estimates give a figure of 50% of the world steel production based on scrap in 2050 (Swedish Steel Producers Association, 2012).

Steel is an alloy and is produced into a large variety of different alloys depending on the application intended for the steel, usually divided into what is labeled low-alloyed steel and high-alloyed steel. Depending on the alloy, steel contain alloying elements like manganese, nickel, chromium, tungsten, titanium, niobium etc., in varying amounts, for high-alloyed steels is from 1% and upward. The alloys are often added as ferroalloys, by which is meant an alloy comprising iron and the alloying element. Ferroalloy production almost always consumes more resources than iron production, and greenhouse gas emissions are, for example, 2–20 times higher for the ferroalloys than for iron.

**TABLE 6.2** Steel Product Lifespan (Brooks and Pan, 2004)

<table>
<thead>
<tr>
<th>Product</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildings</td>
<td>20–60</td>
</tr>
<tr>
<td>Major industrial</td>
<td>40</td>
</tr>
<tr>
<td>Heavy industrial machinery</td>
<td>30</td>
</tr>
<tr>
<td>Rails</td>
<td>25</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>7–15</td>
</tr>
<tr>
<td>Vehicles</td>
<td>5–15</td>
</tr>
<tr>
<td>Steel cans</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

**FIGURE 6.2** The distribution of steel use in emerging and advanced countries across sectors. From World Steel Association.
One type of high-alloyed steel is stainless steel, based on the noncorrosive properties that chromium and nickel introduces to the steel. The simplest stainless steel grade is composed of 18 and 8 wt% of chromium and nickel, respectively, but the chromium content is in some grades much higher and stainless steel is also usually alloyed with Mo, W, Mn etc.

### 6.2 SCRAP PROCESSING AND MATERIAL STREAMS FROM SCRAP PROCESSING

#### 6.2.1 Scrap Classification

Scrap used can be of several different origins, as illustrated in Figure 6.3. Home scrap is the scrap that emanates from recycling within the plant, e.g. reverts from the furnace surrounding, from ladles, from separation of metals contained in slag, melts that has to be recycled due to some specifications that are not fulfilled as well as pieces cut off during heat treatment, rolling and finishing of the products. This type of scrap is usually well sorted into different qualities and with low content of impurity elements, raising the possibility of recycling the scrap back to the production of the same steel quality.

Manufacturing scrap is the scrap coming from the manufacturing of the consumer goods; it can be very well sorted and of high purity and definitely has the potential to be so. Old scrap or obsolete scrap is the scrap coming from spent consumer products or other origins, as collected by the scrap dealers. The scrap is generally sorted into different scrap categories depending on composition and size of the scrap as illustrated in Table 6.3.

As mentioned earlier, steel has a high recovery of collected scrap. However, as also is obvious from the sorting specifications given in Table 6.3, the steel scrap is very seldom sorted into different alloys, thus the recovery of alloying elements into the same type of steel is much lower.

#### 6.2.2 Scrap Processing

Larger scrap from, e.g. cars, white wares and WEEE, is usually treated in a shredder, cf. Figure 6.4, where the scrap is fragmented into smaller pieces with the aim of obtaining different materials in separate pieces to facilitate sorting. A typical process scheme for the upgrading and sorting of different materials from the shredder is given in Figure 6.5.

The steel scrap is loaded into the shredder and fragmented into about hand-sized pieces. Very small and light particles, mainly with organic content, is pneumatically conveyed and collected as a dust. The material then passes a number of separation steps, at a minimum consisting of magnetic separation, sieving and air separation, whereby the majority of the steel is collected in the magnetic fraction, nonferrous metals are collected in the nonmagnetic fraction and very small and light particles are separated from the scrap fractions. These process steps can then be complemented with a number of different separation steps to improve the sorting: density separation, weak magnetic separation, eddy-current separation, hand sorting, automatic sorting based on color or physical properties, etc.

Typically the material coming from the shredder is not completely separated. Pieces
with steel together with copper, aluminum or other metals are quite common (e.g. van Schaik, 2004; Reuter et al., 2005, van Schaik et al. 2002), and depending on the sorting process a piece with, e.g. steel together with copper, might either end up in the steel or copper material after sorting due to inappropriate liberation in the shredding or due to inappropriate particle size for the separation process used. Copper content in steel scrap is one thing that limits the possible steel qualities that can be produced, an issue that will be further discussed in Section 6.5. For the moment we can simply just note that the requirements on impurity content in the final steel is very much dependent on the steel quality produced, from above 0.3\% Cu to below 0.1\% Cu for different steel grades. Therefore, the tradition has been that steel qualities with very low limits on copper content, which usually also have a higher price, are produced in ore-based steelmaking, the ore usually having low copper content. Copper content in steel scrap from a shredder plant has been about 0.25\% to 0.3\% and rising. An interesting observation is that

<table>
<thead>
<tr>
<th>Category</th>
<th>Specification</th>
<th>Density</th>
<th>Cu</th>
<th>Sn</th>
<th>Cr, Ni, Mo</th>
</tr>
</thead>
<tbody>
<tr>
<td>Old scrap</td>
<td>E3</td>
<td>≥0.6</td>
<td>≤0.250</td>
<td>≤0.010</td>
<td>Σ ≤ 0.250</td>
</tr>
<tr>
<td></td>
<td>E1</td>
<td>≥0.5</td>
<td>≤0.40</td>
<td>≤0.020</td>
<td>Σ ≤ 0.30</td>
</tr>
<tr>
<td>New scrap</td>
<td>E2</td>
<td>≥0.6</td>
<td>≤0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low residuals</td>
<td>E8</td>
<td>≥0.4</td>
<td>≤0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uncoated</td>
<td>E6</td>
<td>≥1</td>
<td>≤0.30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shredded</td>
<td>E40</td>
<td>≥0.9</td>
<td>≤0.250</td>
<td>≤0.020</td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>E5H</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tunings</td>
<td>E5M</td>
<td></td>
<td>≤0.40</td>
<td>≤0.030</td>
<td>Σ ≤ 1</td>
</tr>
<tr>
<td>High residual</td>
<td>EHRB</td>
<td>≥0.5</td>
<td>≤0.450</td>
<td>≤0.030</td>
<td>Σ ≤ 0.350</td>
</tr>
<tr>
<td>Scrap</td>
<td>EHRM</td>
<td>≥0.6</td>
<td>≤0.40</td>
<td>≤0.030</td>
<td>Σ ≤ 1.0</td>
</tr>
<tr>
<td>Fragmented, from incineration</td>
<td>E46</td>
<td>≥0.8</td>
<td>≤0.50</td>
<td>≤0.070</td>
<td></td>
</tr>
</tbody>
</table>

FIGURE 6.4  Schematic illustration of a shredder.
shredded steel scrap in Sweden has decreasing copper content nowadays, about 0.22% Cu, because the copper has become very valuable, therefore giving an incentive for handpicking of larger copper pieces present in the steel scrap.

Equipment for sorting of scrap based on properties such as color and magnetic properties is already on the market and is to some extent also used by the scrap-treating companies. An alternative is sorting based on the chemical composition as determined, e.g. through spectroscopic techniques. Scrap sorting of aluminum using laser induced breakdown spectroscopy (LIBS) has already proven to work very well (Gesing et al., 2003; Aydin et al., 2004). The use of the same technique for sorting of steel scrap has been tested recently in a research project within the Steel Eco-Cycle program in Sweden (Gurell et al., 2012). The technique has proven to be feasible to rapidly determine different type of steel alloys and works well as an aid at the scrap yard to determine the exact use of different scrap deliveries to optimize the use of alloying elements and not risk contamination by unwanted impurities. The technique is still too slow for use as an online sorting aid at a conveyor belt in a shredder plant.

6.3 THE PROCESSES USED FOR SMELTING STEEL SCRAP

Figure 6.6 illustrates the process scheme for production of steel from both ore and scrap. Scrap-based steelmaking is almost 100% based
Iron ore-based production

Coal → Coking plant → Coke → Iron ore → Blast furnace → Hot metal → Oxygen converter → Scrap-based production

Scrap

FIGURE 6.6 Schematic process scheme of steelmaking based on ores or scrap (Swedish Steel Producers Association, 2011).

Development of the process with slag foaming through injection of a carbon source and oxygen, oxygen lancing, preheating of the scrap, bottom tapping, cocombustion of fuel in burners, etc. has led to a substantial decrease in energy consumption and also has added some flexibility in the use of energy source. Depending on the actual processing technology, electricity consumption for smelting steel scrap in a modern EAF is in the range

FIGURE 6.7 Principals of an Electric Arc Furnace (EAF) for smelting steel scrap.
of 400–450 kWh/t steel. Slag formers are added to take up some of the impurities coming with the steel. The steel is then refined in ladle furnace processes, casted, rolled and finished. A recent trend is that also within scrap-based steelmaking in an EAF, more and more virgin iron units are used, in the form of direct reduced iron (DRI) or hot briquetted iron (HBI), which will be discussed further in Sections 6.7 and 6.8. The furnace can either be operated on AC current with three electrodes, which is the dominating alternative and also the version illustrated in Figure 6.7, or operated on DC current with one electrode.

The EAF is a very efficient smelting unit but not a very good reactor type for carrying out refining reactions or for adding large amounts of nonmetallic material. Scrap smelting in an EAF is thus dependent on subsequent refining to give a high-quality steel.

Ore-based steelmaking, cf. Figure 6.6, is usually based on a sintered ore and coke charged to a blast furnace (BF), where the iron oxides in the ore are reduced to metal. As the material in the blast furnace is always in contact with carbon in coke, the hot metal tapped from the blast furnace will be almost saturated with carbon, typically about 4.5 wt% carbon in hot metal. Some tenths of a percent of silicon will also be dissolved in the tapped hot metal.

After tapping from the blast furnace, the hot metal is usually refined at least from sulfur, sometimes also from phosphorus. The refined hot metal is decarburized with pure oxygen in the converter, usually a BOF. Reactions taking place are:

\[
\begin{align*}
[\text{Si}]_{\text{Fe}} + O_2 & = \text{SiO}_2 (\text{slag}) \\
[\text{C}]_{\text{Fe}} + 1/2 O_2 & = \text{CO} (g) \\
[\text{Mn}]_{\text{Fe}} + 1/2 O_2 & = \text{MnO} (\text{slag}) \\
\text{Fe} + 1/2 O_2 & = \text{FeO} (\text{slag})
\end{align*}
\]

All these reactions are exothermic, generating a lot of heat. Silicon content in the metal will very rapidly decrease to almost zero, whereas carbon content decreases during the whole blow, until the blow is stopped at about 0.05% C left in the steel. Oxidation of Mn and Fe is of course only partial. Hot metal from the blast furnace usually has a temperature of about 1300–1400 °C when it arrives at the converter. As a consequence of the heat evolution from the exothermic reactions, large quantities of coolant have to be added to ensure that the temperature is not raised above approximately 1700 °C. Coolant is either ore or scrap. If scrap is used as coolant the amount added is usually in the range 15–20% of the amount of steel produced. Since the volumes of steel produced in the BF–BOF route are large, the amounts of scrap consumed within what is usually labeled ore-based steelmaking are quite large.

Stainless steel is produced in a process flow similar to the process route illustrated in Figure 6.6 for producing scrap-based ordinary steel except for one important difference. Most stainless steel produced in the Western world is based on scrap melted in an EAF, but because the amount of stainless steel scrap not is enough, also ordinary steel scrap has to be used. The lack of alloying elements such as chromium and nickel in the latter makes it necessary to alloy with ferrochromium and ferronickel or pure nickel. Carbon is then introduced with the ferroalloys and a refining step using oxygen to convert carbon into \(\text{CO}(g)\) has to be introduced, often carried out in an Argon Oxygen Decarburation (AOD)-converter. Stainless steel can be either ferritic or austenitic, a difference that can be of large importance for recycling, as discussed further in Section 6.4.

### 6.4 TRENDS IN QUALITY OF THE SCRAP AVAILABLE FOR STEEL PRODUCTION

Steel is produced in a large number of different alloy compositions containing different amount of alloying elements like Cr, Mn, Nb, B, V, etc. In the final product the steel may be provided with a coating of zinc,
pigments etc. The share of coated steel produced is globally increasing, resulting in an increasing amount of recirculated scrap with different types of coatings. The scrap used in steel making tends therefore to be a more complex material. In conventional scrap melting processes (steel converters or EAF’s), some of the impurities evaporate and leave the process with the off-gas and with particulate matter and are collected in the gas cleaning. Others either are oxidized and report to the slag or are dissolved in the steel, or both.

The average North American car today contains not only more of metals other than steel (Al, Mg, Cu) and more of other materials but also more of speciality alloyed steels, as shown by the difference in composition when data for 1975 and 2007 are compared, cf. Figure 6.8 (Bevans et al., 2013). As can be seen, the share of steel present as mild, low-alloyed steel has drastically decreased. Projections from the automotive industry indicate that the advanced high-strength steels will account for up to 65% of the vehicle’s body and structure by 2020 (Bevans et al., 2013). Some of these steels can contain as much as up to 24 wt% Mn and 6 wt% Al. To be able to also recover the alloying elements with high efficiency will then be of utmost importance.

From 1992 to 2001, the generation of steel packaging increased by 22% in the EU, and an increasing part is recycled (Baeyens et al., 2010). In 2007, the amount of steel used for packaging in EU was slightly less than 5 Mt. The steel used for packaging is mainly of two types: steel coated with a very thin layer of tin or steel coated with chromium and chromium oxide. Both types can also be combined with a polymer film.

When stainless steel is recycled through a shredder plant, the ferritic part of the stainless steel will be collected with the ordinary carbon steel scrap because ferritic stainless steel is magnetic. Whereas the recovery rate of austenitic stainless steel can be expected to be high, much of the ferritic stainless steel will be recovered as carbon steel scrap. Oda et al. carried out an analysis of the substance flow of chromium in steel in Japan and predicted that the mean chromium content in EAF carbon steel will gradually increase and reach 0.24% in 2030 (Oda et al., 2010).

Zinc present as a coating on steel will during melting at reducing conditions evaporate and is collected in the gas cleaning and is not any problem for steel quality. Provided that the zinc content in the dust collected is high enough, the dust is a raw material for extraction of zinc in, e.g. Waelz-kilns and fuming furnaces. In the

FIGURE 6.8 Material composition (wt%) of an average North American vehicle from 1975 to 2007. Adapted from Bevans et al. (2013).
ore-based steel industry, on the other hand, the share of scrap used is lower, and the zinc content is not at a level where extraction of zinc is economically feasible. In this case, the zinc content becomes an obstacle for internal recycling of dust and sludge to the blast furnace, which cannot tolerate high zinc loads.

6.5 HINDRANCES FOR RECYCLING—TRAMP ELEMENTS

6.5.1 Definition of Tramp Elements

Tramp elements are those elements that are present in steel, but usually not intentionally added, and are difficult to refine from the steel, and therefore will be kept in the steel cycle once entered, coming back over and over again when steel is recycled. Some of these have detrimental effects on the steel properties, others being alloying elements for some steel grades, but not for all. As iron is a quite un-noble metal, not as e.g. aluminum, but still, the iron will react with a refining agent before the tramp element reacts, thereby making refining from these elements difficult. For the elements defined as tramp elements no commercially feasible refining processes exist today. Figure 6.9 illustrates common elements in steel, how they are used and controlled and which ones that usually are referred to as tramp elements.

Sources for tramp elements can be many, ore, scrap, reductants used, fluxing agents or coming with alloying additions. Usually the ore used has much less impurity content than the scrap used, although depending of the ore, some impurities may come with the ore, like Cr, As and Cd. The behavior of several impurity and tramp elements during oxidation in, e.g. the BOF process, is illustrated in Table 6.4 (Vallomy, 1985).

As Figure 6.9 shows, some of these elements are added intentionally as alloying elements in certain steel grades, like Mo, Cr, Ni and Cu, but are detrimental for the quality of the steel in other steel grades or are lost to the slag in the processing of another type of steel grade. Low-alloyed steel is often produced by melting the scrap in quite oxidizing conditions, resulting in a substantial loss of chromium to the slag even when chromium-containing low-alloyed steel is produced. Stainless steel can either be ferritic or austenitic stainless steel or both, and as ferritic stainless steel is magnetic it will report to the ordinary carbon steel fraction during separation after shredding. In the upgrading from a shredder plant, steel scrap is not sorted to any larger extent than into an ordinary steel fraction and a stainless steel fraction. Also, in the

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![Figure 6.9](image-url)  
*Common elements in steel, how they are used and which ones that are referred to as tramp elements.*
manufacturing industry, it is very seldom that the scrap is sorted into various types of alloys and depending on the content of alloying elements. This means that in addition to containing tramp elements that have detrimental influence on the steel quality, alloying elements valuable in the production of some steel grades might get lost.

6.5.2 Influence on Steel Quality by Tramp Elements

Copper is known to induce surface cracks during hot rolling if reheating is carried out in oxidizing atmosphere (Vallomy, 1985), at contents above 0.15% (Marique, 1996). Presence of Sn has the same effect at a content higher than 0.05 wt% and a combination of Cu + Sn enhances the effect. The presence of these elements is also responsible for an increased probability for transverse cracking during continuous casting (Mintz, 1999). The mechanism of crack formation due to copper is due to a preferential oxidation of iron at the surface and liquid copper precipitating at the steel surface when the copper content in remaining austenite exceeds the solubility limit. The liquid copper is wetting the iron and thus easily penetrates into the austenite grains, giving rise to the cracks (Kajitani et al., 1996). By increasing the Sn content, the domain of liquid phase is widened, which is why Sn increases the probability of crack formation (Yamamoto et al., 2006). Marique (1996)
showed that the rejection rate due to crack formation during wire rod rolling was drastically increased at copper content above 0.15%. The crack depth was shown to increase with increasing reheating temperature above 1000 °C and increasing copper content (Kajitani et al., 1996). Decreased silicon content in the steel also increases the upper temperature limit for crack initiation (Kajitani et al., 1996). Calvo et al. (2007) have shown that the width and depth of the cracks depend on both the reheating cycle and the as-received condition, i.e. the condition from the caster.

Several tramp elements have a negative effect on cold forming and cold drawing, e.g. Sn, Cu, As and Cr. The upper limit for copper and tin for deep drawing grades is 0.1 and 0.02%, respectively (Vallomy, 1985). Ductility deteriorated when testing was performed in oxidising atmosphere (Mintz et al., 1995) and it was proposed that observed precipitation of Cu$_2$S was responsible and that an equal amount of nickel could prevent this from happening. In inert atmosphere the influence of Cu on hot ductility is confusing, with no clear conclusions. Another phenomenon reported is that increased nickel content has been shown to reduce the scale removability from rolled steel (Asai et al., 1997).

These are only a few examples, and excellent reviews of the existing knowledge on influence of tramp elements on steel properties can be found in the literature (e.g. Vallomy, 1985; Marique, 1996; Herman and Leroy, 1996; Mintz and Crowther, 2010).

6.5.3 Importance of Tramp Elements for a Sustainable Recycling of Steel

There was much focus on tramp elements in steel, especially during 1980s and 1990s, but not as much later on. This period was characterized by stagnant level of world steel production and a rapidly increasing share of steel produced from scrap. Scrap sorting and knowledge about the rate for accumulation of tramp elements was not very well developed and hence steel producers looked on increasing levels of e.g. copper in the steel scrap with fear. In this century steel production has increased rapidly and hence a larger portion of steel is produced from ores. Scrap sorting has become more efficient, and the increased prices for metals like copper has even made hand-picking of larger copper pieces from the steel scrap on the conveyor belt in the shredder plant economically feasible. Thus, e.g. copper content in the shredded scrap has not continued to increase but instead decreased on average. Nevertheless, scrap-based steel producers sometimes need to dilute the steel scrap with virgin iron units from HBI or DRI, if they are producing steel grades with very low tolerance for tramp elements. If and when the world once again comes into a situation with small or no increase in the consumption of steel and the share of scrap-based steelmaking is increasing, the question of how to handle the tramp elements will once again be of fundamental importance for sustainable recycling of steel.

6.6 PURIFICATION OF SCRAP

6.6.1 Dezincing of Galvanized Scrap

Two main principles are used, leaching and thermal treatment. Leaching in both acid solutions (HCl, H$_2$SO$_4$) and in basic solution (NaOH) is discussed in the literature (Sen and Roy, 1975; Niedringshaus et al., 1992; Koros, 1992; Rome, 1992; Ijomah and Ijomah, 2003). When removing zinc at high pH, Zn is transferred to Zn$^+$ and recovered either in the form of sodium zincates (Na$_2$ZnO$_2$ or NaHZnO$_2$) precipitated from a saturated solution or zinc recovered by electrolysis. In acid leaching, zinc is recovered via a saline solution of Zn(NO$_3$)$_2$, ZnSO$_4$, or ZnCl$_2$. Leaching at high pH is a selective process which not affect the iron, but is a
time-consuming process, while acid leaching is less selective but much faster. Since leaching is a surface reaction, the surface area available becomes important and the leaching proceeds much faster for shredded scrap than for bundles. A leaching process with a treatment time of 6 h at high pH with high, >90%, recovery of the zinc through electrolysis was described by Niedringshaus et al. (1992). Formation of cyanide was indicated as one possible problem. One commercialized process, the Meretec process, is based on this concept. The concept is said to be competitive and fully functional.

Several studies describe thermal treatment of scrap. The possibility of evaporating Zn, Ni, Cr and Sn from coated materials using chlorine is one alternative (Dapper et al., 1978). Because ZnCl₂ is more stable than FeCl₂ and the ZnCl₂ is much more volatile, a selective evaporation of Zn can be obtained as long as there is metallic Zn present. Rinsing of noniron oxides and metals using HCl from the combustion of PVC has been described by Fray (1999). Tee and Fray have shown that to selectively evaporate compounds in the coatings oxychlorination with controlled ratio of O₂:Cl₂ in the gas mixture is necessary (Tee and Fray, 1999a,b; Tee and Fray, 2005). Zn boils at a temperature of 906 °C, and it has been shown that vaporization of zinc in CO/CO₂ and N₂ gas mixtures is very rapid and almost complete at temperatures higher than 850 °C (Ozturk and Fruehan, 1996).

Another alternative for removing highly volatile compounds present in coatings on steel is vacuum treatment. A method to clean scrap by heating and vacuum treatment was suggested by Okada et al. (1995). High removal efficiency was obtained already at 700 °C as compared to preheating with CO/CO₂ gas mixtures. Almost 97% zinc recovery was achieved.

Steel scrap is often preheated before charging to the EAF. This has several purposes: (1) to decrease the meltdown time in the EAF, (2) to remove water and especially in cold climates to remove ice, which otherwise can result in violent gas explosions and (3) if waste heat can be used, this will result in an overall saving of the energy need. However, the presence of halogens and organic matter together with the scrap may result in the formation of dioxins and furans and therefore preheating temperature is according to regulations in e.g. Sweden limited to 300 °C in conventional scrap preheating equipment. Possibilities to increase the scrap preheating temperature to temperatures where a simultaneous evaporation of e.g. zinc can be obtained would have many benefits for the steel industry. This concept has been studied by Larsson et al. (2012) in a project in the Swedish research program “The Steel Eco-cycle” (Steel Eco-cycle, 2013) and is also part of an ongoing European research project financed within RFCS (Research Fund Coal and Steel).

The idea is to separately combust energy-containing waste as auto shredder residue (ASR) with oxygen. The hot gas is used for preheating scrap. Off-gases from this preheating are partially recirculated and mixed with gases from the combustion to control the temperature of the hot gases entering the scrap preheating, but also giving enough gas volumes to ensure rapid enough preheating. Preheating of the scrap is controlled at <900 °C in a separate shaft reactor. Exhaust gases are cleaned and chlorides are captured.

Results from the small-scale tests showed that chlorine-rich gases, e.g. exhaust gases, from ASR combustion can be a suitable gas for cleaning and preheating scrap (Larsson et al., 2012). Pilot tests have shown that it is possible to achieve a uniform scrap preheating at 650 °C, where the zinc removal efficiency is high. Preheating to 650 °C generates a metal loss of less than 1%. The process concept, including oxyfuel combustion, dedicated gas scrubbing and exhaust gas recirculation, has been proved. The low gas volumes and low amount of gas vented to the surrounding will allow for treatment of the gas and the removal of harmful elements in a cost-efficient manner.
A number of different methods to remove zinc from surface coatings of steel have been proposed during the years but very few have yet reached a commercial stage. For new methods to be commercially introduced, they have to be cost-competitive with the traditional way of dealing with zinc in steel scrap, namely the processing of zinc rich dust from the EAF in Waelz kilns, the dominant process route, or, e.g. in a zinc fuming furnace. The low zinc content in the dust from ore-based steelmaking makes it very expensive to send the dust for zinc recovery. The strategy for many ore-based steel producers has therefore been to purchase only comparably clean scrap as coolant. Market shortness of clean scrap in the future would perhaps make the ore-based steel industry interested in scrap rinsed from zinc, if the prices can be comparable with the cost for use of ores as coolant.

6.6.2 Detinning of Steel Scrap

Electrolytic detinning of tinplate scrap has been in commercial use for a long time. Scrap pressed into bundles serve as anodes immersed in a caustic soda bath at about 85 °C. Tin is deposited on a steel cathode as a sponge material, which is scraped off (Savov and Janke, 1998). The tin content in the steel is below 0.02 wt% after this processing. The process requires rather large volumes to be economical and is claimed to be suitable only for prompt scrap. Because the process is a surface process, it will be applicable only where tin is present as a surface coating. A proposed alternative method for detinning tinplate scrap has been to react the surface with a sulfur-containing gas at moderate temperature to form a tin sulfide layer. The tin content in the steel could be decreased to levels of about 0.1 wt% from above 0.3% originally. At higher temperatures the diffusion of tin from the surface layer and into the steel becomes fast and limits the possibilities for detinning based on surface reactions. Other proposed methods include selective evaporation or by oxidizing (Savov et al., 2000).

6.6.3 Others

It is technically and sometimes also economically quite possible to refine steel from metals or impurities present as a surface coating using leaching or evaporation techniques because these methods are acting on the surface. For impurities or tramp elements present in the steel alloy, it is a different question. Although sometimes detrimental for the properties of the steel, the content in the steel is low, a few hundredths up to a few tenths of weight percentage, and thus they have a low thermodynamic activity. Furthermore, iron is sometimes the least noble metal. Both factors make it difficult to find a suitable reagent. In addition, steel has a comparably low value per tonne and the volumes of steel scrap are huge in comparison with other metals, necessitating a refining concept to be very cost effective.

Many different processes for refining steel from copper have nevertheless been proposed, including dissolution in a solvent like Al, Pb, sodium sulfide—iron sulfide, soda-iron sulfide or aluminum sulfide—iron sulfide, reacting with a chlorinating agent or vacuum treatment of the steel. The thermodynamics of the removal of tramp elements from steel scrap was evaluated by Tsukihashi (2003). The conclusion was that calcium—metal halide fluxes have an excellent refining ability. No figures were given on the amount of different tramp elements that possibly could be removed. None of these suggestions have, however, reached a commercial stage. Several aspects of tramp element control in steel have been studied by a group of steel producers and research institutes in the European Union (Boom and Steffen, 2001).

To give one example, the high distribution of some impurity elements to a lead phase in contact with a carbon-containing iron phase could
be utilized (Yamaguchi and Takeda, 2003a,b). A miscibility gap exists between an iron phase with 95.4%Fe–4.5%C–0.1%Pb and 99.9% Pb–0.1%Fe. Copper, tin, zinc, gold, silver and palladium are primarily distributed to the lead phase. An equal amount of iron and lead makes 70% of the copper and tin contained in the iron to report to the lead phase. The temperature for the study was 1453 K. The quite high amount of lead needed to dissolve a considerable amount of copper and tin makes such a process dependent on the value of recoverable noniron elements, not only for the purpose of cleaning the steel scrap.

6.7 TO LIVE WITH IMPURITIES

In a world with an increased share of steel produced from scrap, the issue of the impurity content in the scrap will be of high importance. The question is illustrated in Table 6.5 showing the typical content of impurity elements (given as the sum of content in wt% of the elements Cu, Sn, Ni, Cr, Mo) in different types of raw materials, as well as the limits for the content of these impurity elements for the production of different type of steels.

Table 6.5: Typical Content of the Impurity Elements Cu, Sn, Ni, Cr, Mo (Given as the Sum of These Elements in wt%) in Different Type of Raw Materials for Production of Steel and the Requirements for Production of Different Steel Grades

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Total Impurity Content in wt% (Sum of Cu + Sn + Ni + Cr + Mo)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct reduced iron</td>
<td>0.02</td>
</tr>
<tr>
<td>Pig iron</td>
<td>0.06</td>
</tr>
<tr>
<td>No. 1 factory bundles</td>
<td>0.13</td>
</tr>
<tr>
<td>Bushelling</td>
<td>0.13</td>
</tr>
<tr>
<td>No. 1 heavy melting</td>
<td>0.20</td>
</tr>
<tr>
<td>Shredded auto scrap</td>
<td>0.51</td>
</tr>
<tr>
<td>No. 2 heavy melting</td>
<td>0.73</td>
</tr>
</tbody>
</table>

**STEEL GRADE**

- Tin plate for draw and iron cans: 0.12
- Extra deep drawing quality sheet: 0.14
- Drawing quality and enameling steels: 0.16
- Commercial quality sheet: 0.22
- Fine wire grades: 0.25
- Special bar quality: 0.35
- Merchant bar quality: 0.50

Adapted from Vallomy (1985).

6.8 MEASURES TO SECURE SUSTAINABLE RECYCLING OF STEEL

Steel is, based on volume, the most recycled metal, and there exists a well-functioning business structure for the recycling of steel. Losses are inevitable in the processing and handling of any metal. Losses occur to byproduct streams and waste in the processing (slag,
dust, sludge) and into other material cycles, material fractions aimed for energy recovery or into waste that is landfilled. These losses can and will be decreased as technology develops and as awareness of the issue grows among all the stakeholders involved in the production of products, from designers to manufacturers. The amount of collected steel that is lost from the recycling cycle is nevertheless probably small in comparison with the total production. Not at least if metal prices increase in comparison with the living standard, what is worth recycling will be recycled. If and when the increase in world consumption of steel decreases, there will be greater possibilities of producing a large amount of the steel from recycled scrap.

The largest question for the steel and scrap processing industry in order to obtain long-term sustainable steel recycling is perhaps the question of scrap quality and avoiding quality losses when recycling steel. As the share of steel produced from ore has increased in the last decade, accumulation of tramp elements has not been an issue of high importance recently, but it is an issue that will have to be tackled in the future.

Several actions can be taken to minimize the detrimental effects of tramp elements:

- Design for recycling
- Improve sorting at the shredder plant
- Improve processing at the steel plant
- Live with impurities based on development of new alloys
- Dilute scrap with ore-based iron units
- Improve the understanding of steel flow in the society

*Design for recycling.* By proper choice of materials placed together in different parts of a construction and by the choice of fittings between different materials, it is possible to ensure a good separation of crucial parts, by manual dismantling or in the following shredding and processing of the scrap (Reuter et al., 2005). Although design for recycling has been on the table within the research communities dealing with sustainability and recycling for long time, the impression is that the issue has not yet really reached the designers and construction engineers. Issues on appearance, functionality and manufacturing are still considered more important.

*Improved sorting at the shredder plant.* Techniques for sorting of scrap where physical properties or composition is utilized have been developed and new techniques will surely emerge. Hitherto, more advanced sorting techniques have not been implemented at larger scale, possibly because the steel producers are not willing to pay for the extra cost through an increased scrap price and also because the need has not been there, as “pure” ore-based iron units are cheaper. Rem et al. (2012) has shown by the introduction of a shape-sensitive magnetic separator that it is possible to pre-sort scrap into two products. One product is a bulky, thin-walled steel fraction of high purity, the other a volumetrically small flow of heavy parts containing the contaminants. The latter is very well suited for cost-effective hand sorting or sensor sorting.

A better knowledge of the composition of the scrap will increase possibilities to utilize the scrap for production of the same type of alloy, thereby not only securing the recycling of iron units but also securing a better utilization of the alloying elements and decreasing the losses of the same.

*Improved processing at the steel plant.* Direct casting of thin strips or in-line strip production (ISP) is a technique that will give higher tolerances for impurity elements such as copper due to a faster cooling and making a reheating procedure unnecessary (Arvedi, 2010; Spitzer et al., 2003).

However, as long as not all steel would be produced in these new thin-strip casting processes, steels produced with higher content of e.g. copper would have to be kept in a separate recycling loop.
To live with impurities through development of new alloys that can accept a higher content of impurity and tramp elements. Although introducing detrimental properties in many steel grades with the present processing of steel, some of the tramp elements are also used as alloying elements for some steel grades to improve corrosion resistance and enhance the mechanical properties.

It is possible to improve the properties of steel by precipitating nanoscale copper sulfides (e.g. Liu et al., 2006, 2007; Yamamoto et al., 2006) through a rapid solidification and/or controlling the balance between Cu, S and Mn content or by adding phosphorus, which promotes precipitation of copper sulfide from ferrite instead of from austenite and suppresses precipitation of MnS at higher temperature. Precipitation of copper sulfide is preferable compared to MnS. From a steel recycling point of view, it must, however, be noted that the copper content in the alloys studied is low, below 0.1 wt%. In extra-low-carbon titanium added interstitial free steel sheet, Cu is the useful alloying element for increasing hardness. Addition of Cu or Cu + Ni at a level of 0.5 and 0.4 wt%, respectively, has been shown to increase the volume fraction of retained austenite and to improve elongation and the strength ductility balance (Kim et al., 2002, 2003).

As pointed out regarding ISP technology, if the new alloys developed contain substantial amounts of tramp elements and as long as many steel grades require a very low content of tramp elements, it has to be possible to keep these steels in a separate recycling loop by well-functioning collection and sorting.

Dilution of scrap with ore-based iron units. The last choice will, as it already is, be to dilute impure scrap with ore-based iron units produced in the form of DRI or HBI.

Finally, an improved understanding of steel flows in the society, on a steel grade level, would give us a tool to model the possible accumulation of tramp and impurity elements depending on reasonable scenarios for future economic and technological development. Many Material Flow Analysis (MFA) and Substance Flow Analysis (SFA) studies of the steel flow have been carried out, but very few on steel grade level. Some exceptions exist (e.g. Oda et al., 2010) where the recycling of different types of stainless steel was analyzed.

References


6. RECYCLING OF STEEL


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