cubic" (fcc). This means that the atoms of copper occupy the edges of a cube and in addition the centers of each area between the edges. That gives in result the highest density in a package, as 72% of the room is filled and the outer electrons can flow relatively easy from one atom in the lattice structure to another, leading to the excellent electrical conductivity of copper. Furthermore, this structure also allows that copper can be rolled to foils. So all metals which can be rolled to foils have this "copper structure" like silver and gold.

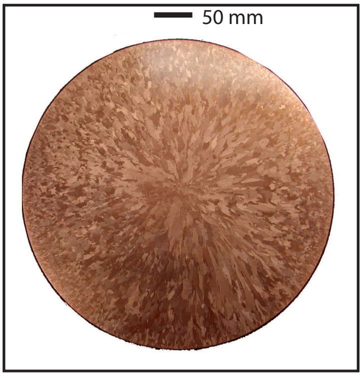

Figure 2.1.3: Grain Structure of a Cast Copper Billet (Source: Aurubis AG, www.Aurubis.com)

In theory, the crystal structure should be infinite and ideal by a repeating "fcc"-structure, but in reality it is neither ideal nor infinite, as there are always dislocations and distortions in the crystal structure. Furthermore, massive copper in practical applications never consist of only one crystal ("single crystal copper") but of a lot of small crystals - the grain structure. According to the number and intensity of the imperfections in the crystal structure slight different mechanical properties like hardness or strength can result. The grain structure depends on the pretreatment of copper and on the conditions of solidification of copper from a melt. If a melt is cooled down rapidly, copper crystallizes in a fine grain structure, whereas if cooling is very slow, coarse crystals are formed. In Figure 2.1.3 it can be seen that a cast copper billet has at its outer border a finer grain structure than in the middle, because solidification starts rapidly at the outside and grows more slowly to the center of the billet. If a copper melt is solidified within less than a second, no crystallites are formed but an amorphous material like a glass is formed ("metallic glass").

Element	Elect. Conductivity [S/m]	Elect. Conductivity [% IACS]
Silver	$61.4 \cdot 10^6$	105.9
Copper	$\mathbf{59.1 \cdot 10^6}$	**101.9**
Aluminum	$36.6 \cdot 10^6$	63.1
Iron	$10.0 \cdot 10^6$	17.0
Lead	$4.7 \cdot 10^6$	8.1
Stainless Steel	$1.4 \cdot 10^6$	2.4
Graphite (parallel to layers)	$3 \cdot 10^6$	5.2
Titanium	$2.6 \cdot 10^6$	4.4

Table 2.2: Comparison of Electrical Conductivities of Elements

dard for 100 % conductivity in IACS-units[1]. Very pure copper exhibits with $59.1 \cdot 10^6$ S/m an even higher conductivity of 101.9 % IACS. As silver is too expensive and has only a 5% higher conductivity, copper is the most important metal, if electrical power has to be transported with the lowest losses.

The reason for the high conductivity of the metals is the capability of the outer electrons to move relatively free through the lattice in the crystal (see Figure 2.1.2). Whereas the positive ions of the metals are placed on fix positions in the crystal, the small electrons move like a gas. So the electrons form an "electron cloud". If a voltage is put between two positions on the metal the cloud moves leading to an electric current.

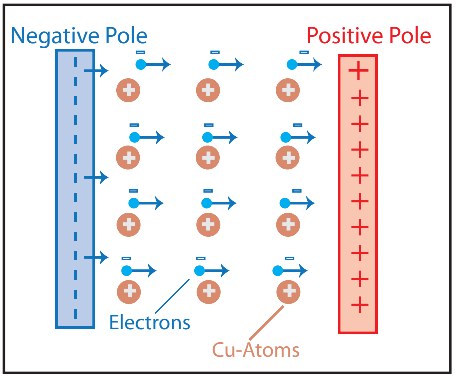

Figure 2.2.4: Mechanism of Electrical Conductivity of Copper

[1]International Annealed Copper Standard

cheap ammonium nitrate. By the distances of the drill holes and the amount of explosives the particle size of the broken ore can be influenced within certain limits. The exploitation by blasting is done in a way that a series of benches are formed which winds down into the open pit. The benches are used as working areas and haul roads. The rocks are then transported by truck or conveyor to a central crushing and milling plant. In modern mines the locations of the blasting holes are defined by GPS (Global Satellite System).

Figure 5.1.1: Structure of an Open Pit mine: Chuquicamata in Chile (Source: B. Langner)

Second Step: Particle Size Reduction (Comminution) As the copper ore is grown together with the gangue, the rocks from blasting have to be crushed and milled to a size where its copper mineral grains are separated from the non-copper-minerals grains. Furthermore, the particle size also has to be optimized for the subsequent flotation separation process. This is done in several steps. In the first step the material is crushed with a jaw or a Gyratory crusher to a particle size of about 20 cm. This material is then fed to secondary crusher where it is crushed down to a size of a walnut. The next step is a wet grinding process by adding about 20 % water in rotating 'tumbling mills' where abrasion, impact and compression all contribute to breaking the ore. This is normally

In the sixth place there is Glencore, which in former times was only a trading company, but has in the meantime bought some copper mines.

Anglo American - number seven - founded 1917 as a gold mining company is also diversified and the biggest producer of platinum in the world. Besides copper and platinum Anglo American is active in diamonds, nickel, iron ore and coal.

Grupo Mexico in the eighth position was originally in 1942 a engineering company. Today their main product is copper and the associated metals like molybdenum and silver. But they have also activities in zinc, lead and gold.

Number nine is KGHM in Poland which is a pure copper and silver company mining ores mainly in Poland.

Russian Norilsk Nickel - number 10 - is by value mainly a nickel and platinum company even if they produce more copper than nickel.

5.1.6 Cost Structure of Copper Concentrate Production

The main cost factors of a mine are financing costs, operating costs, administration cost, license costs (royalties) to the country of the mine and depreciation and amortization. To compare the cost of different copper mines, mainly the cash costs are compared.

In the cash cost model of a copper mine the total costs are considered from ore to copper cathode. If a mine does not produce cathodes, then also the treatment and refining charges (TC/RCs) given to the smelter and refinery are considered as cash costs. The cash costs includes mining costs, milling costs, royalties and administration costs of the mining site, but no costs of the headquarter. Cash costs do not include financing costs and depreciation and amortization. Some times cash costs are also termed “direct costs ” abbreviated as C1.

A special feature of the cash costs calculation of a copper mine is that the value of the by-products is deducted from the final cash cost of the metal. For example, if a copper mine produces molybdenum or gold as a by-product, then the value of the molybdenum and gold produced will be deducted from the cash cost of the copper. This is the usual accounting treatment for by-products in most industries. That leads sometimes to the curious effect that for some mines cash costs can be negative, as the value of the by-products is higher than than the cash cost of a mine.

As an example for calculating different costs the cost model for the Codelco mines is shown in table 5.6.

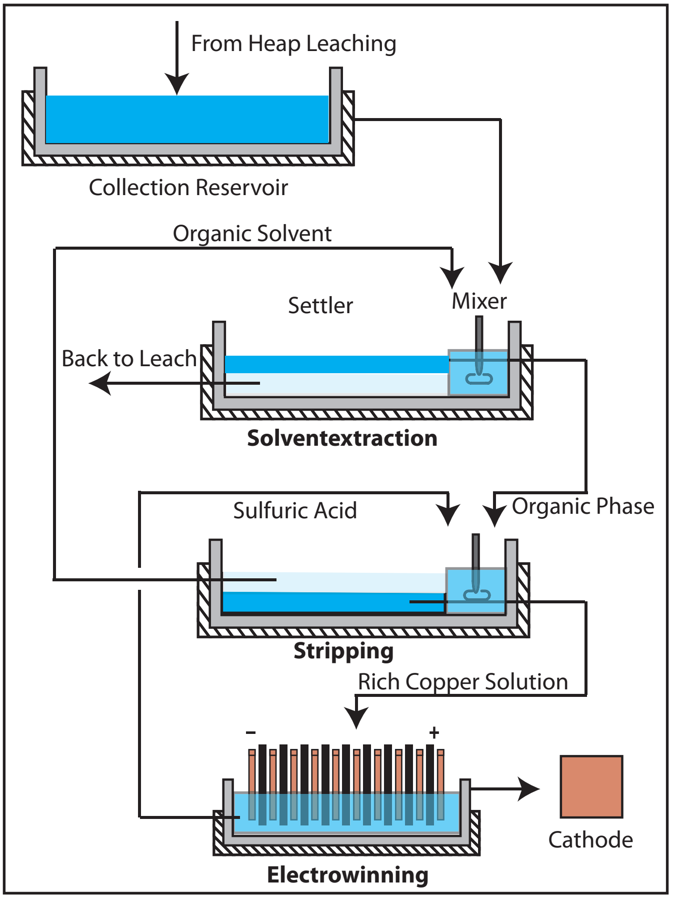

Figure 5.2.4: Flowsheet of Solventextraction/Electrowinning

5.2.6 The biggest Copper Leaching Operations

Whereas about one third of the whole copper mine production in the world is located in Chile, for the SX-EW production of copper it is even two third of the production which is based in Chile. Besides the high reserves of oxidic and secondary sulfidic copper, the dry arid climate in most regions in Chile is an important issue for SX-EW.

Nevertheless, the biggest SX/EW plant in the world is the Freeport Mc Roan owned Morenci mine in Arizona, where 2009 about 390.000 t of cathode copper

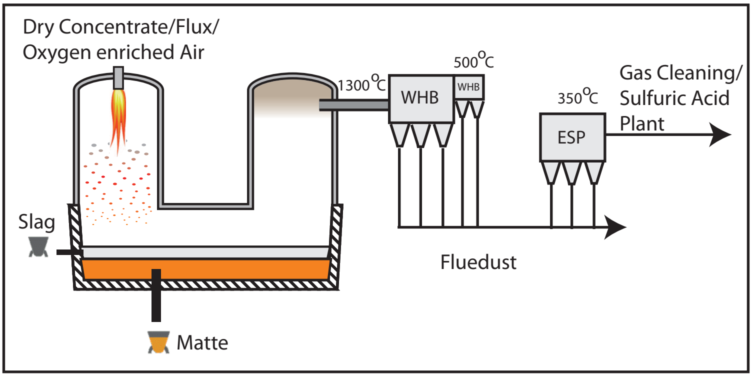

Figure 5.3.5: Principle of the Outokumpu (Outotec) Flash Furnace

The process bases on the small particle size of the concentrate of only 50-150 microns. So the dried concentrate with about 25-35 % copper is burned in a burner with air or oxygen enriched air similar to a coal burner on the top of a shaft. The concentrate burners (usually 1, but up to 4) combine dry particulate feed with oxygen enriched air and blow them downward into the hearth furnace. During the falling through the shaft the fine concentrate particles react to copper matte and the sulfur and partly iron is oxidized, evolving a lot of heat and melting the solids. A very important issue is cooling the reaction shaft to prevent the rapid wear of the chrome-magnesia brick lining because of the high temperature. The mix of slag and matte is collected in the hearth of the furnace for settling and separating matte and slag phase. Water-cooled copper block tap holes are used for periodically removing molten matte and slag. At the end an uptake removes hot sulfur dioxide and dust containing off gas.

The products of flash smelting are: molten matte at 55-65 % copper, molten iron-silicate slag containing 1 to 3% copper and hot dust-laden off gas containing a high concentration of 30-70% sulfur dioxide depending on oxygen enrichment. According to the enrichment of oxygen in the air the process can be run autogenous without adding fuels to the shaft. Nevertheless some fuel is used in the settling part of the furnace to enable a constant temperature of about 1250 °C.

The sizes of the furnace vary: e.g. in a year 2000 design the hearth is 18 m long, 6 m wide and 2 m high. It has a 4.5 m diameter, 6 m high reaction shaft and a 5 m diameter, 8 m high off gas uptake. It has one concentrate burner by the industry is the precipitation with ferric chloride but in some plants also the precipitation as calcium arsenate is used.

It involves the formation of an insoluble ferric arsenate ("jarosite type") compound which is allowed to sediment at the bottom of tailings or residue ponds. It appears to be stable for many years in the proper environment which includes slightly acidic and oxidizing conditions. So it can be deposited in certain areas and is safe for a lot years. The earlier method by precipitation with limestone has shown evidence that calcium arsenate compounds decompose very slowly in contact with atmospheric carbon dioxide, but may be used also if stored under closed conditions.

In most of the smelters also slags have to be disposed, if there is no usage for the iron silicate material or if the slag is ground after a flotation process. But as the leachability of the slag is slow, there is - in normal iron silicate slags - no direct danger for the environment by the disposal of these slags. Even if all the slags have to be deposited, the smelting process typically produces less than three tons of solid waste per ton of copper produced. If the slag is used as product because of its quality and a market next to the smelter the waste is much lower. E.G. 2009 in Hamburg in total 17,000 t of waste has to be disposed, from which about 12,800 t have been classified - mainly because of the arsenic content - as hazardous and are safely stored in old salt mines. That means a very low waste formation of only 30 to 40 kg/ ton of copper.

5.3.11 Energy consumption of Smelting and Refining

Smelting and refining facilities require large amounts of energy, notably the fuel energy used for drying, heating, smelting, fuming, melting and transportation, and the electrical energy used in electrolysis, for the production of oxygen and for powering utilities and equipment. One big step in reducing the energy consumption of smelting and refining of copper was made with the Outotec ™ flash furnace technology because it is possible to operate the process autogenous, that is smelting only by the use of the reaction heat. As the gases are capsuled in the waste heat boiler the energy which is in the off gas can be recovered to produce high pressure steam and electrical power.

Nevertheless, even the flash furnace technology uses fuels for heating the settling furnace. In the converter process the reaction heat is used to melt reverbs or scrap without using additional fuel. These are examples in which the industry has optimized energy consumption. Nevertheless, some processes have got in the meantime the physical limits where additional substantial energy savings are possible. The reduction of energy is in nearly all smelters a focus of optimization - as energy and labor cost are the main cost positions with

Figure 6.1.1: Different Kinds of Copper Containing Scraps (Source: B.Langner@Aurubis AG, www.aurubis.com)

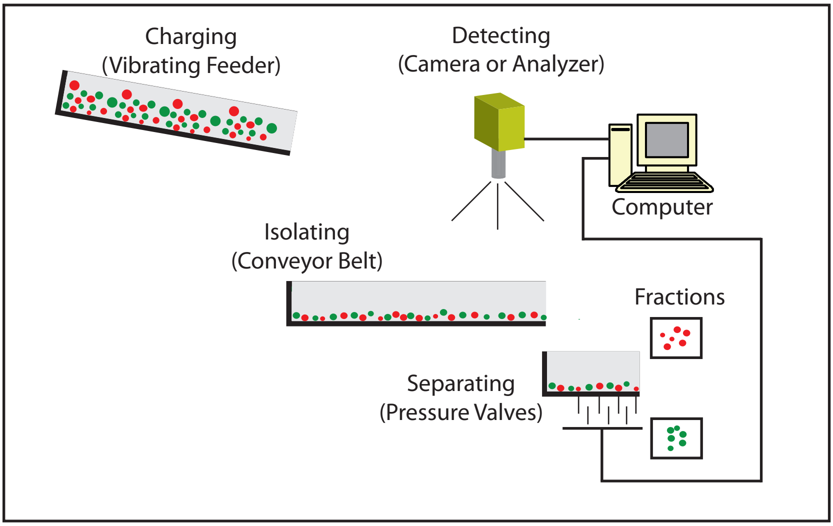

Figure 6.2.6: Illustration of Automatically Sorting

In recent last years, automatic sorting processes have been developed, where not only the analysis of the parts by optical or spectroscopic procedures is done, but also the separation of single parts from a conveyor belt can be done (see figure 6.2.6). The new automatic sorting processes use different analyzes or the different color of the parts by identifying different materials, leading to a very good separation of two or three different fractions. In one technology the different materials are blown with air to the one or other direction according to the analysis. With the development of high speed computers even single particles with a diameter of some millimeters can be separated.

Sampling of Complex Material For high-grade electronic scrap not only mechanical separation is important but also sampling. In contrast to normal copper scrap, where estimation of the copper content is the common method for analyzing the copper content in the scrap, printed circuit boards may contain not only copper but also high amounts of precious metals. For example, a high value printed circuit board from a computer may contain up to 400 g/t of gold, representing a value in the range of 15,000 USD, whereas pure copper has a value in the range of 10,000 USD. So the value of the gold content may be higher than the value of pure copper. Therefore, sampling by grinding and dividing the sample is a very important and difficult procedure, recquiring sophisticated procedures and experience. Sampling costs are therefore for

7 The Copper Cathode - Base of the Copper Business

All copper - independent if produced from secondary smelting, from heap leaching or from smelting copper concentrates - is at the end electrorefined. So the final product of copper production is always the copper cathode. Therefore the copper cathode is the base for the production of copper products and the base for the price of copper.

Figure 7.0.1: Copper Cathodes (Source: B.Langner@Aurubis AG, www.aurubis.com)

A cathode is a nearly square sheet with an area of about $1m^2$. The weight of cathode depends on the process. If the cathode is produced by starter sheets of copper the weight is about 100 to 150 kg. If it is produced by stainless steel blanks, where copper is grown on both sides and separated into two cathodes, the weight is about 50 kg to 75 kg. Normally, cathodes are bundled to a weight

In developing countries with a lower demand for copper rod, Upcast plants are also used for normal wire applications. Especially in China there exist a lot of similar plants , although more and more Southwire®, Properzi®or Contirod®plants are erected.

Dip Forming technology Dip Forming is another technology to produce oxygen free (or at least oxygen poor) copper rod. In the last years there have not been any new installations of the dip forming process, but there are still some plants in operation. The principle of dip forming is also different from all the other process. A copper wire of about 2 mm with a clean shaved surface is passed at high speed through a molten copper bath, then the copper solidifies around the cold wire (called mother rod) and emerges from the bath with a larger diameter of 2.5 times the cross section of the mother rod. This rod is hot rolled in a controlled atmosphere. After rolling about 40 % of the rolled wire is recycled for the next solidification. With capacities of about 50,000 tons, the capacities of dip forming plants are in between of the Upcast®and the Southwire®/Contirod®technology.

8.1.2.3 Economics of wire rod production

The specific production cost of rod are relatively low compared to cathode production, as the big plants are running at high capacities and fully automated. Nevertheless, the biggest cost factor in rod production is energy, mainly for the melting of cathodes and for the rolling of the cast bar, although the processes have optimized in the last years to lowest energy consumption. As there are no big steps in new technologies expected and cathodes have to be melted as the first step, the rising energy costs are an important factor for the global competition. Wire rod is a commodity, which is traded globally. Nevertheless it has advantages to sell copper rod in short distances to the customers as transport costs may play an important role.

The price of copper rod consists of the price of cathodes according to LME and the cathode premium and the surcharge for converting copper cathodes into rod. The surcharges for copper rod are only about 2-5 % of the copper price depending on the actual quotations. With the increase of the copper price, financing costs have become very important. Especially, if the rod plant is a stand alone plant, cathodes have to be bought and financed over a long time. With a yearly interest rate for the copper, which is higher than the surcharge for wire rod, the duration of financing the copper becomes more and more an important issue. Beside stand alone rod plants, there are also a lot of rod plants, which are integrated into a smelter and refinery. This is an advantage,

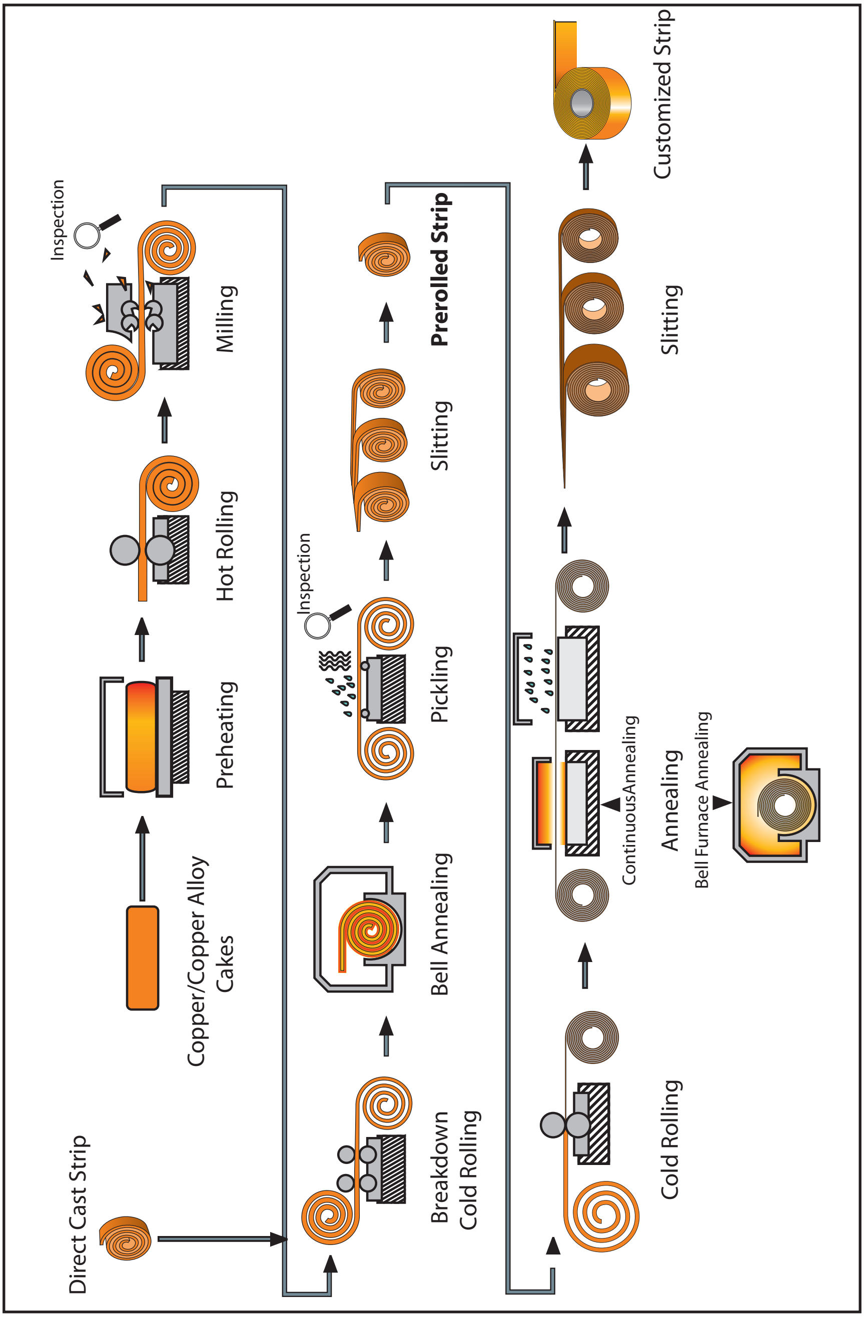

Figure 8.3.7: Flowsheet of the Production of Strip (Source:Aurubis, www.aurubis.com)

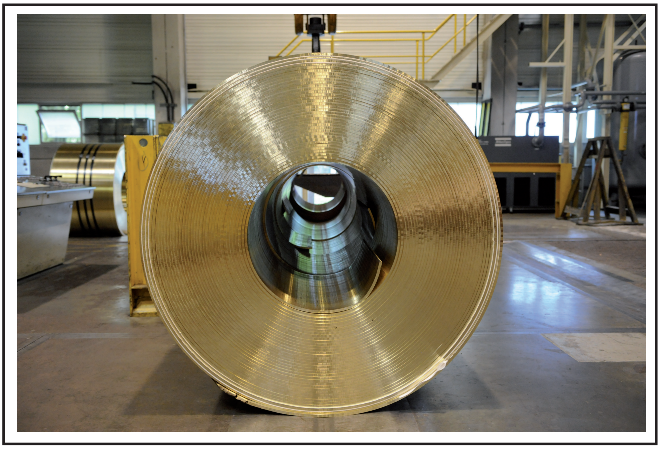

Figure 8.3.29: Big Brass Coil with a specific Coil Weight > 20 kg/mm (Source: B.Langner@Schwermetall, www.schwermetall.de)

into the final semis product. These includes costs for casting, hot rolling or hot extrusion, cold rolling or drawing, annealing and slitting. The main cost factors are labor and energy costs.

The second very important cost factor is scrap. Especially in the strip production, but also in the production of tubes and profiles the scrap rates are high. Whereas in wire drawing only 1-5 %, in strip production the scrap rate from cathode to strip may be as high as 50 %. If the strip is stamped afterward, one finds in the final application only 20% of the original produced copper or copper alloy cake. Therefore, it is important that the scrap is recycled as soon as possible. If the casting furnaces and the production of the final semi is not at the same location, there are either transport costs for the scrap or the scrap has to be sold to a local scrap dealer.

To have a low scrap rate in strip production it is important to have big coil weights. With a 25 tons cake specific coil weights can be achieved a specific coil weight of up to 20 kg/mm. But compared to wire rod with an assumed coil weight of 6 tons and a diameter of 8 mm the specific coil weight is about 750 kg/mm. Therefore, the production of products from rod instead from cakes lead to a much lower scrap rate if a whole coil is processed in one step.

The third factor are investment costs. In the strip production the production costs decrease with increasing specific coil weight. To process such big coils, very big machines are used for hot rolling with a width of up to 1250 mm and a weight of more than 20 tons. Therefore the hurdle for a new production is very

Transformer and Converter	5,000 kg
Power generator	2,400 kg
Azimuthal driving system	200 kg
lightning protection system	100 kg
Medium Voltage Cable	400 kg
Rotor Blades	120 kg
Others	75 kg
SUM	**8,295 kg**

Table 9.1: Copper Use in a Big Windmill (Source: Aurubis AG www.aurubis.com)

does not blow all over the year with the same power. Therefore other energies or storage power stations are needed to secure a safe supply of energy for the households and the industry. As in the sea the wind blows much more and more steady, in the last years the development of of offshore wind farms has got a big importance.

Windmills need a lot of pure copper. As also the traditional centralized power generators needs copper the demand for copper in windmills is much higher. As an example a windmill with a power of 5 Megawatt needs more than 8 tons of copper. Copper is needed in different parts of the wind mills as shown in table

The main copper content is in the transformer and in the generator. By moving the rotor blades into the direction of the wind copper is also needed. Then there is copper in the cables within the wind mill. Furthermore, there is even more copper also for the distribution of power from the windmills, as much more cables are needed than in big traditional power plant, as power generation is much more distributed.

Offshore windmills need even more copper in thick cables to transport the power from the wind farm in the open sea to the coast. Furthermore, because of corrosion by the salt content also copper alloys like copper nickel are used in constructional parts of an offshore windmill.

In total, with the growth of power generation by wind mills the demand for pure copper will grow in the next decades. So copper is an essential material for the production of power from wind energy.

9.1.1.3 Electrical Power from Photovoltaic Energy

Photovoltaic is the next important renewable energy. Although photovoltaic does not need copper containing generators as the electrical power is produced

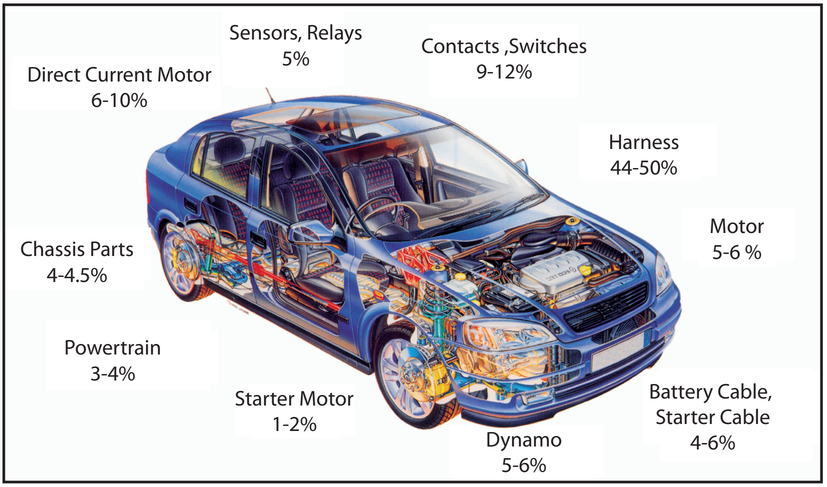

Figure 9.1.7: Copper in a Car - 100% = 25 kg (Source: Deutsches Kupferinstitut, www.kupfer-institut.de)

the windows which account for 5 to 10 %. Another 5-6 % is in the alternator or dynamo, also 5-6 % are in the motor and about 10 % in the switches and contacts. So it is not possible to build a car without copper, even if parts may be substitutable by aluminum. Beside the electrical conductivity the biggest advantage of copper is the reliability even during conditions of high vibrations.

9.1.3.2 Copper in other Transportation Industries

Copper plays an important role in all motor driven vehicles.

So an average motorized farm vehicle uses 29 kg of copper, while construction vehicles use an average of 30 kg. An electric forklift truck uses about 63 kg copper. About 4.1 tons of copper is contained in a Boeing 747-200 jet plane. Included in that weight is about 175 km of copper wire. A typical, diesel-electric railroad locomotive uses about 5 tons of copper. More than 8 tons of copper is used in the latest and most-powerful locomotives.

All these examples shows that copper is the driving force not only for the development of the intelligent use of energy but also for moving everything from one place to another.

10 Economics from Copper Ore to Final Application

10.1 The Value Chain of Copper

Copper goes through a series of steps, before it is mounted into the devices for its final use. As the copper industry is splitted into different specialized companies concentrating mainly on a fraction of the whole value chain, there are intermediate products, which are sold to the subsequent fraction of the value chain. There are only a few companies which are active in all links of the chain. But even in these companies capacities in the different links do not have the same capacities so that these companies sell intermediate products to third parties, which also may be competitor for the subsequent step. Examples are Freeport McRoan who produces wire rod and some semis, but sells also cathodes as the cathode production is much bigger than their semi production. Another example is Aurubis, which is active in the whole value chain from copper concentrate to semis, but the capacities of the semi production is smaller than the production of the first use of copper cathode products. So Aurubis sells shapes also to semi fabricators. This is a different situation in the aluminum industry, which is much more integrated than the copper industry as all big aluminum producers are integrated from the mine to the products. So a big aluminum company like Alcoa or Hydro Aluminum not only mines the raw material bauxite, but also produce aluminum foils for packaging of food.

In an expanded sense also the recycling of end-of-life copper products is a part of the value chain of copper.

10.1.1 Revenues in the Value Chain of Copper

Starting with the copper deposit the first step is recovering the ore. But copper ore is not a tradable product, as it contains only 0.3-2 % copper. So it does not make sense to bring the material to other locations. Therefore, the added value of mined copper cannot be calculated. The first tradable product with a market price is copper concentrate with a copper content of about 20-30%.

competitive - in spite of the higher reliability of electrical copper installations and connections - in some years, if the ratio copper/aluminum remains in the same range or does even grow.

Therefore, an artificially high copper price especially in comparison with other materials - e.g. from speculations of the funds - is a danger for the use of copper on the long run.

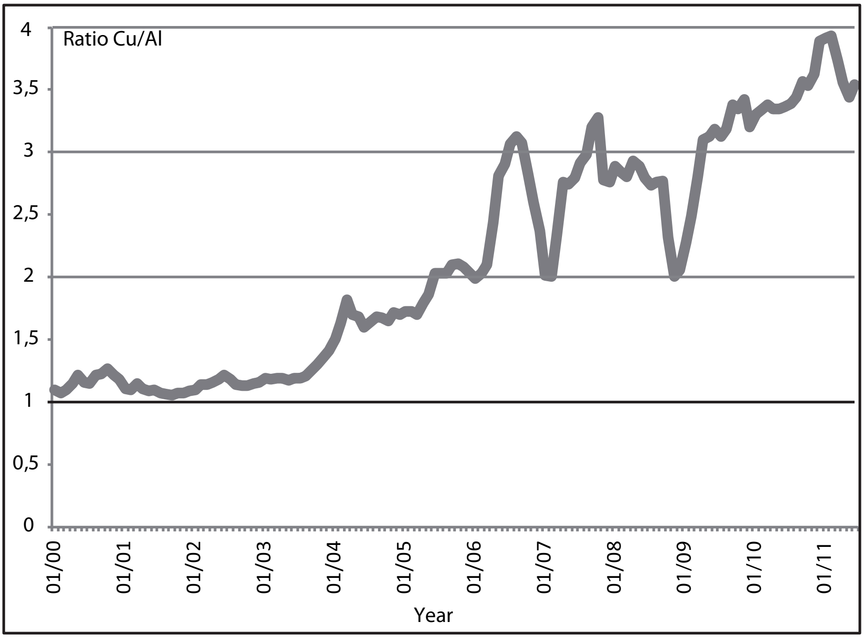

Figure 10.2.2: Ratio Copper/Aluminum Price (Source: Aurubis AG, www.aurubis.com)

10.2.2 Financing of Copper - Working Capital in the Value Chain of Copper

With the increasing copper price financing of copper in the value chain becomes a much bigger importance than before. So process have to be optimized mainly to the operating costs - which was the rule before - but also to the financing costs. At these higher copper prices for some mass products financing costs are higher than production cost, as in the copper price is as five times higher than 10 years before.