aluminium technologies

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syllabus

- Attendance is encouraged!
- Don’t panic if you are late! Sneak in!
- Mobile phones only in silent mode!
- Be involved in classroom discussions! I’d be happy to answer your questions.
- No office hours: You can drop by anytime for questions, discussions!
<table>
<thead>
<tr>
<th>week #</th>
<th>subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 / 29.9</td>
<td><strong>Introduction to aluminium; distinctive features of aluminium; primary production, production of alumina (Bayer Process); production of aluminium metal (Hall-Heroult Process)</strong></td>
</tr>
<tr>
<td>2 / 6.10</td>
<td>Melting aluminium; furnaces; crucibles; melt contamination (impurities in aluminium melts); melt treatment procedures-degassing.</td>
</tr>
<tr>
<td>3 / 13.10</td>
<td>melt treatment-degassing; fluxing, flux types; filtration, filter types; grain refinement; modification; alloying; mixing</td>
</tr>
<tr>
<td>Week #</td>
<td>Subject</td>
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<tr>
<td>4 / 20.10</td>
<td>Assessment of melt quality; Hydrogen and inclusion measurements, modification rating; thermal analysis; K-mold; chemical analysis/OES, fluidity, die soldering; gating and feeding aluminium castings</td>
</tr>
<tr>
<td>5 / 27.10</td>
<td>Assessment of casting quality; macro and micro examinations: grain size, SDAS, porosity,</td>
</tr>
<tr>
<td>6 / 3.11</td>
<td>Advantages of aluminium casting; foundry alloys; alloying elements; alloy groups, designations</td>
</tr>
<tr>
<td>7 / 10.11</td>
<td>Casting processes; HPDC, LPDC, GDC, sand casting, rheo-thixo casting; alloy selection for casting process; applications of foundry alloys; heat treatment of castings</td>
</tr>
<tr>
<td>week #</td>
<td>subject</td>
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<td>---------</td>
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</tr>
<tr>
<td>8 / 17.11</td>
<td>Semi-continuous casting process (DC casting); extrusion processing; solution and aging heat treatments; aluminium profiles</td>
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<tr>
<td>9 / 24.11</td>
<td>continuous casting processes; Hot-cold rolling of aluminium; foil rolling; TRC and TBC</td>
</tr>
<tr>
<td>10 / 1.12</td>
<td>TRC and TBC (cont’d); wrought alloys; effect of alloying elements; alloy groups; applications; temper designations; selection of alloys</td>
</tr>
<tr>
<td>11 / 8.12</td>
<td>midterm</td>
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<tr>
<td>week #</td>
<td>subject</td>
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<td>---------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>12 / 15.12</td>
<td>Forging of aluminium alloys; thixoforging; aluminium foil; converted foil; packaging applications; aluminium foam; aluminium powder metallurgy; anodising; corrosion of aluminium alloys</td>
</tr>
<tr>
<td>13 / 22.12</td>
<td>Metallography and microstructure of aluminium alloys</td>
</tr>
<tr>
<td>14 / 29.12</td>
<td>presentations</td>
</tr>
<tr>
<td>15 /</td>
<td>presentations</td>
</tr>
</tbody>
</table>
grading

Presentation-term paper  20%
Midterm  30%
final  50%

Course grade  100%
Presentation themes
You are expected to write a comprehensive review article on
- Additive manufacturing of aluminium automotive components
- Manufacture of aluminium foams
- Non-equilibrium processing of aluminium alloys (ECAP, ARB, FSP)
- Recycling of aluminium dross
Are you ready?
Aluminium metal

Low density, strength, recyclability, corrosion resistance, durability, ductility, formability and conductivity make aluminium a valuable material. Due to this unique combination of properties, the variety of applications of aluminium continues to increase.

We cannot fly, go by high speed train, high performance car or fast ferry without aluminium. We cannot get heat and light into our homes and offices without it. We depend on it to preserve food, medicine and provide electronic components for our computers.
**Aluminium**

**Discovery date:** 1825  
**Discovered by:** Hans Oersted  
**Origin of the name:** The name is derived from the Latin name for alum, 'alumen' meaning bitter salt.

**Fact Box**
- **Group:** 13  
- **Period:** 3  
- **Block:** p  
- **Atomic number:** 13  
- **State at room temperature:** Solid  
- **Electron configuration:** [Ne] 3s²3p¹

**Properties**
- **Atomic number:** 13  
- **Electron configuration:** 1s²2s²2p⁶3s²3p¹  
- **Atomic weight:** 26.98 g  
- **Density:** 2.7 g/cc  
- **Melting point:** 2.375 g/cc  
- **Melting point:** 660 °C  
- **Boiling point:** 2519 °C  
- **Crystal structure:** FCC

**Carbon steel**  
Carbon steel: 2.5–3  
1% carbon steel: 4  
White iron: 4–5.5  
Gray iron: – 2.5 (expansion to 1.6)  
Ductile iron: – 4.5 (expansion to 2.7)  
Copper: 4.9  
Solidification contraction partial: Cu-30% Zn: 4.5  
Solidification contraction partial: Cu-10% Al: 4  
Solidification contraction partial: Aluminum: 6.6  
Solidification contraction partial: Al-4.5% Cu: 6.3  
Solidification contraction partial: Al-12% Si: 3.8  
Solidification contraction partial: Magnesium: 4.2  
Solidification contraction partial: Zinc: 6.5
Properties of Aluminium

Oxidation states: +3, +2, +1  \((1s^22s^22p^63s^23p^1)\)

Electronegativity: 1.610
Electron affinity: 41.747 kJ/mol
Atomic radius: 1.43 Å
Atomic volume: 10.0 cc/mol
Lattice constant: 4.049 Å

“This valuable metal possesses the whiteness of silver, the indestructibility of gold, the tenacity of iron, the fusibility of copper, the lightness of glass. It is easily wrought, is very widely distributed, forming the base of most rocks, is three times lighter than iron, and seems to have been created for express purpose of furnishing us with the material for our projectile.”

Jules Vernes, “From the Earth to the Moon”, 1865
brief history

- It was only in 1808 that Sir Humphrey Davy, the British electrochemist, established the existence of aluminium, and it was not until 17 years later that the Danish scientist Oersted produced the first tiny pellet of the metal.

- Al metal was first displayed at the Paris Exhibition in 1855.

- aluminium was more precious than gold, silver or platinum at that time.

- Napoleon III became enthusiastic about the possibilities of this new material, mainly for military purposes.
Brief history

- Deville a Frenchman was subsequently able to produce aluminium at a cost of 37 $/kg but that was still too high to launch the metal commercially.
- Thirty years later improvements in production methods made in association with Hamilton Y. Castner, an American chemist, had lowered the price to 18 $/kg.
- The metal was still potentially plentiful and useful but, even at this substantially reduced price, too expensive for general use.
- The total annual output at this time was only 15 tonnes.
Two unknown young scientists - Paul Louis Toussaint Héroult of France and Charles Martin Hall of the United States - searched for the low-cost production of aluminium. They worked separately, each unaware of the other’s activities, in their respective countries. In 1886, the two scientists - almost simultaneously - came up with the same new process. Named as Hall-Heroult process!
Brief history

- The first World War had a dramatic effect on aluminium production and consumption.
- In the six years between 1914 and 1919 world output soared from 70,800 to 132,500 tonnes.
- After the very large expansion occasioned by WW I the ground was held.
- Once the changeover to civilian production had been carried through the increased capacity was occupied before very long in supplying the normal demands of industry. And this happened again, on a much larger scale, as a result of the WW II.
Brief history

- World production of primary aluminium increased from 704,000 tonnes in 1939 to a peak of 1,950,000 tonnes in 1943, after which it declined considerably.

- At the end of World War II, the western world industry had completed a threefold expansion in capacity in the space of four to five years.

- Civilian markets had to be developed for this new capacity. The demand for aluminium proved to be elastic and the expanded facilities were working at near capacity in a matter of a few years.
Aluminium facts...

- Aluminum is the most widely used metal after iron.
- The primary source of aluminum is bauxite.
- Aluminum is paramagnetic.
- The top three countries that mine aluminum ore are Guinea, Australia and Vietnam. Australia, China and Brazil lead the world in aluminum production.
- Aluminum was once called the "Metal of Kings" because pure aluminum was more expensive to produce than gold until the Hall-Heroult process was discovered.
Aluminium facts...

A piece of jewelry in the tomb of the 3rd Century Chinese general Chou-Chu has been found to contain 85% aluminium.

Aluminum is used in fireworks to make produce sparks and white flames. Aluminium is a common component of sparklers.

About 80% of the mass of an aircraft is aluminium.

Not any more!!
Boeing dreamliner!!
Atomic structure

Al has the atomic number 13. According to present concepts, this means that an aluminium atom is composed of 13 electrons, each having a unit negative electrical charge, arranged in three orbits around a highly concentrated nucleus having a positive charge of 13. The 3 electrons in the outer orbit give the aluminium atom a valence or chemical combining power of +3.
Crystal structure

Aluminium, like copper, silver and gold, crystallizes with the face-centred-cubic arrangement of atoms, common to most of the ductile metals. This means that the atoms form the corners of a cube, with one atom in the centre of each face. The face centred cubic structure is one of the arrangements assumed by close packed spheres, in this case with a diameter of $4.049 \times 10^{-8}$ cm, the corners of the cube being at the centre of each sphere.
Properties - low density

- Lightness is the key characteristic of aluminium
- $2.7 \text{ (g/cm}^3\text{)} = 1/3$ the weight of steel
- The addition of other metals does not appreciably change the density (plus 3%, minus 2%), except in the case of Lithium alloys where the density of the alloy is reduced by up to 15%.
- Low weight is an advantage during assembly in buildings and in many other applications.
Low density

- Weight is important for all transportation applications.
- Use of aluminium in vehicles reduces dead-weight and energy consumption while increasing load capacity.
- Low weight means reduced emissions of greenhouse gases and pollutants.
- Low weight combined with the high strength possible with special alloys has placed aluminium as the major material for aircraft construction for the past sixty years.
Low density

Mercedes' M-133-55
Low density

Volume per Unit Weight

- Aluminium: 1
- Steel: 0.346
- Copper: 0.303
- Brass: 0.32
- Monel: 0.307
- Titanium: 0.6
- Magnesium: 1.55
strong

- Tensile strengths between 70 and 700 MPa.
- Unlike most steel grades, aluminium does not become brittle at low temperatures. Instead, its strength increases.
- Aluminium alloys increase in strength without loss of ductility.
- The strength of the metal can be increased by alloying. Mixed with small amount of other metals, it can provide the strength of steel, with only one-third of the weight.
strong

iPhone 6s
super-strong '7xxx'
aluminium
Ductile - Easy to form

- Aluminium is ductile
- Easy to process in cold and hot condition
- This allows design flexibility and integration in advanced transport and building industries
- Its ductility allows products of aluminium to be basically formed close to the end of the product’s design.
Highly corrosion resistant

Aluminium naturally generates a protective oxide coating and is highly corrosion resistant. Different types of surface treatment such as anodising, painting or lacquering can further improve this property. It is particularly useful for applications where protection and conservation are required.
The electrical conductivity of 99.99% pure aluminium at 20°C is 63.8% of the International Annealed Copper Standard (IACS).

However, twice as good a conductor as copper based on weight.
The addition of other metals in aluminium alloys lowers the electrical conductivity of the aluminium. Heat treatment also affects the conductivity since elements in solid solution produce greater resistance than undissolved constituents.
The very good electrical properties of aluminium have made it an obvious choice for applications in the electrical industry, particularly in power distribution where it is used almost exclusively for overhead transmission lines and busbars. The first major aluminium transmission line was completed in 1898 in the USA.
Excellent thermal conductor

The thermal conductivity, \( \kappa \), of 99.99% pure aluminium is 61.9% of the IACS, and again because of its low specific gravity its mass thermal conductivity is twice that of copper. The thermal conductivity is reduced slightly by the addition of alloying elements.
Long life - low maintenance!

- All materials suffer degradation from weather conditions, corrosion and decay.
- Aluminium forms a protective oxide coating that is immediately reformed if cut or scratched that makes it highly corrosion resistant; it is very well suited to surface treatments such as anodic oxidation.
- This prolongs the life of aluminium in cars and buildings.
- Reduces need for maintenance.
- Reduces environmental impacts due to replacements and maintenance.
Long-lasting

All materials suffer degradation from weather conditions, corrosion and decay. Aluminium’s natural ability to resist these influences better than many materials is one of its most widely appreciated features. The durability of aluminium applications, such as in building structures, clearly demonstrates this.
Non-magnetic

Aluminium alloys are very slightly paramagnetic, as it has a magnetic permeability slightly greater than one. The low magnetic characteristic of aluminium is of value in military ship structures where it has advantages of lightness and lower cost over other non-magnetic metals. It is also used to advantage in electronic equipment for screening and as heat sinks, usually in the form of finned extruded profiles. Aluminium is often used in magnet X-ray devices to avoid interference of magnetic fields.
Cryo-tolerant

In contrast to steel, titanium and many other materials that become brittle at very low (cryogenic) temperatures, aluminum remains ductile and even gains strength as temperature is reduced. This property makes aluminum highly useful in very cold climates and for transporting extremely cold materials such as liquefied natural gas (-162°C).
Aluminum alloys can be joined by all appropriate major methods, including welding, riveting, mechanical connections, and adhesive bonding. Features facilitating easy jointing are often incorporated into profile design. Fusion welding, Friction Stir Welding, bonding and taping are also used for joining.
Fire-proof/non-combustible

- Aluminium in buildings, construction and transport is fire-proof
- Will only burn if shaped as a very thin film
- Will melt at 660° C without releasing any gases
Great reflector

- Can reflect both heat and light
- Plain aluminium reflects about 75% of the light and 90% of the heat radiation that falls on it. Combined with its light weight, this makes aluminium ideal for reflectors like light fittings, rescue blankets
- High energy efficiency in the reflectors reduces energy consumption
- Combined properties of high reflectivity and low emissivity give rise to the use of aluminium foil as a reflective insulating medium
Great reflector
Reflectance and emissivity

The emissivity of the aluminium surface can be raised considerably by anodic treatment. Clear anodic coatings raise the emissivity to between 35 and 65%, the phosphoric and chromic acid methods being the most effective in this respect. Black anodic coatings have an even greater effect and raise it as high as 95%.

an ideal material for reflectors in, for example, light fittings or rescue blankets.
Perfect for food packaging

- Aluminium foil is completely impermeable - no taste, aroma or light gets in or out
- Non-toxic and odorless
- Widely used in food and drink packaging
- Efficient conservation of food reduces wastage
- Low weight reduces packaging and energy consumption in transportation
- Impermeability also reduces cooling needs
Perfect for food packaging
Completely impermeable and odourless
Aluminium foil, even when rolled to just a 0.007 mm thickness, is still completely impermeable and lets neither light, aroma nor taste substances in or out. Moreover, the metal itself is non-toxic and releases no aroma or taste substances which makes it ideal for packaging sensitive products such as food or pharmaceuticals. Aluminium is therefore widely used in food and drink packaging.
Easy to recycle

- Aluminium is 100% recyclable with no downgrading of its qualities.
- Re-melting of aluminium requires little energy; total loss in the re-melting process is less than 3%.
- Only 5 percent of the energy required to produce the primary metal initially is needed in the recycling process.
- About 75% of all aluminium ever produced is still in use; infinitely recyclable!
Other properties

Linear expansion
Compared with other metals, aluminium has a relatively large coefficient of linear expansion. This has to be taken into account in some designs.

Machining
Aluminium is easily worked using most machining methods - milling, drilling, cutting, punching, bending, etc. Furthermore, the energy input during machining is low.
Screening EM radiation (EMC)

Tight aluminium boxes can effectively exclude or screen off, reflect electromagnetic radiation. The better the conductivity of a material, the better the shielding qualities. Aluminium is the material of choice for enclosures radio-operated equipment but also all electrical and electronic devices, equipment and systems in respect of electromagnetic compatibility.
Primary production
reserves

the most abundant (8.3% by weight) metallic element and the third most abundant of all elements (after oxygen and silicon). Because of its strong affinity to oxygen, it is almost never found in the elemental state. Instead it is found in oxides or silicates. It constitutes about 7.8 wt% of the earth’s crust.
Elements found in earth’s crust

- 47% Oxygen
- 8% Aluminum
- 2.1% Magnesium
- 2.6% Potassium
- 2.8% Sodium
- 3.6% Calcium
- 5% Iron
- 28% Silicon
- 0.14% Others

Titanium, Manganese, Nickel, Copper, Zinc, Lead
Bauxite

Aluminium is produced from bauxite, which contains 40 to 60 wt% impure hydrated aluminum oxide (aluminum oxide with attached water molecules!)

The other components of bauxite typically include:

- Iron oxide
- Silicon oxide
- Titanium oxide
- Water

© Bauxite from Little Rock, Arkansas
## Typical bauxite composition

<table>
<thead>
<tr>
<th>Component</th>
<th>wt%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$_2$O$_3$</td>
<td>30-60</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>1-30</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>&lt;0.5-10</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>&lt;0.5-10</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>0.02-1.0</td>
</tr>
<tr>
<td>CaO</td>
<td>0.1-2</td>
</tr>
<tr>
<td>V$_2$O$_5$</td>
<td>0.01-0.10</td>
</tr>
<tr>
<td>ZnO</td>
<td>0.002-0.10</td>
</tr>
<tr>
<td>Ga$_2$O$_3$</td>
<td>0.004-0.013</td>
</tr>
<tr>
<td>Cr$_2$O$_3$</td>
<td>0.003-0.30</td>
</tr>
<tr>
<td>S</td>
<td>0.02-0.10</td>
</tr>
<tr>
<td>F</td>
<td>0.01-0.10</td>
</tr>
<tr>
<td>Hg (ppb)</td>
<td>50-1000</td>
</tr>
</tbody>
</table>

![Bauxite: Typical Composition -Majors](image)
Other minerals

Feldspars, micas and clay contain $\text{Al}_2\text{O}_3$ between 15 and 40 wt%.
Bauxite mining

- The richest and most economical bauxite ores are often found close to the earth’s crust in tropical and subtropical areas.
- Worldwide reserves of bauxite ores are estimated to last for another 500 years at recent consumption rates.
- Clays and other minerals could, if necessary, provide an almost limitless source of alumina.
Bauxite mining

The vast majority of world bauxite production is mined from open surface pits, by conventional digging machinery, while the rest, mainly from Southern Europe and Hungary, is from underground excavations.

World production: $130 \times 10^6$ tons/year
70 % in Australia, Guinea, Brazil and Jamaica
Bauxite mining

Alcan Quebec, Canada

Alcan Australia
Bauxite mining

The area affected by bauxite mining is about 160 m²/kt.
The original flora and fauna of much of the land involved in bauxite mining is restored once mining operations have ceased. For all forest areas used for bauxite mining, 80% is returned to native forests, the rest is replaced by agriculture, commercial forest, or recreational area, thereby making the area more productive for the local community. As far as rain forests in particular are concerned, however, the area used for bauxite mining in rain forests is almost totally reverted back to rain forest.
Bauxite mining

Bauxite output in 2005 shown as a percentage of the top producer (Australia - 59,959,000 tonnes)
## Bauxite reserves

<table>
<thead>
<tr>
<th>country</th>
<th>Bauxite reserve</th>
<th>Share from world reserves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gine</td>
<td>8,6 Milyar ton</td>
<td>%23</td>
</tr>
<tr>
<td>Avustralya</td>
<td>7,9 Milyar ton</td>
<td>%21</td>
</tr>
<tr>
<td>Vietnam</td>
<td>5,4 Milyar ton</td>
<td>%14</td>
</tr>
<tr>
<td>Brezilya</td>
<td>2,5 Milyar ton</td>
<td>%7</td>
</tr>
<tr>
<td>Jamaika</td>
<td>2,5 Milyar ton</td>
<td>%7</td>
</tr>
<tr>
<td>Çin</td>
<td>2,3 Milyar ton</td>
<td>%6</td>
</tr>
<tr>
<td>Hindistan</td>
<td>1,4 Milyar ton</td>
<td>%4</td>
</tr>
<tr>
<td>Guyana</td>
<td>900 Milyon ton</td>
<td>%2</td>
</tr>
<tr>
<td>Yunanistan</td>
<td>600 Milyon ton</td>
<td>%2</td>
</tr>
<tr>
<td>Surinam</td>
<td>600 Milyon ton</td>
<td>%2</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>400 Milyon ton</td>
<td>%1</td>
</tr>
</tbody>
</table>
Bauxite reserves in Turkey

Estimated total: 68,910,000 tons
Milas, Muğla / Seydişehir, Konya / Akseki, Antalya /
Saimbeyli, Adana / İslahiye, Gaziantep / Hassa, Hatay
production of aluminium from bauxite

Bauxite has to be processed into pure aluminium oxide (alumina) before it can be converted to aluminium metal by electrolysis. This is achieved through the use of the Bayer chemical process in alumina refineries.

Bayer process patented in Germany in 1888 by Joseph Bayer!
Production of aluminium from bauxite

Bayer process is used to produce alumina from bauxite (process patented in Germany in 1888 by Joseph Bayer!)

Hall-Heroult process is employed to produce aluminium from alumina
Commercialization in 1886 Pittsburg Red Co. (Alcoa)
Benefication may be employed via washing, depending on the state and the quality of the bauxite. Bauxite is prepared for the caustic treatment by crushing into smaller pieces.

Caustic treatment “digestion”
Filtration
Precipitation
Calcination
Alumina production

**Beneficiation**

- Bauxite
- NaOH
- Crusher
- Digester
- Red Mud Residue

**Digestion** → filtration → precipitation → calcination
Caustic treatment “digestion”

- Crushed, washed and dried bauxite is treated with caustic soda (NaOH) at high temperatures, under high vapour pressures.

\[
\text{Al}_2\text{O}_3 + 2\text{NaOH} + 3\text{H}_2\text{O} \rightarrow 2\text{NaAlO}_2 + 4\text{H}_2\text{O}
\]

- Aluminium oxide inside bauxite is converted into soluble sodium aluminate, dissolves in caustic soda and is thus separated from the other insoluble oxides.

- Concentration, temperature and pressure in the digester are adjusted according to the characteristics of the bauxite mineral.
Caustic treatment “digestion”

- for minerals rich in Gibbsite; T=140°C
- for minerals rich in Boehmite: 200-240°C
- pressure: approximately 35 atm at 240°C.
- while high temperatures appear to be favourable, corrosion risk increases!
  - other oxides may start to dissolve in caustic at high temperatures!
filtration

- While alumina is dissolved in the caustic soda, insoluble impurities are retained in RED MUD.
- This mixture is filtered to remove the red mud, which is then discarded.
- The clarified alumina solution is transferred to tanks called “precipitators.”
precipitation

- Hot alumina solution is allowed to cool inside the precipitator.
- Aluminium hydrate in the caustic liquoir solution is precipitated:
  
  \[ 2\text{H}_2\text{O} + \text{NaAlO}_2 \rightarrow \text{Al(OH)}_3 + \text{NaOH} \]

- Sodium aluminate solution is seeded with crystals of hydrated aluminum to promote the formation of aluminum hydrate particles.
- As the seed crystals attract other crystals in the solution, large clumps of aluminum hydrate begin to form.
The precipitated aluminium hydroxide is collected at the bottom of the tank and is removed.

Hydrate crystals are grouped according to their size.

Fine crystal fraction is returned back to precipitation step.

The insoluble mud from the precipitator is washed to recover the caustic soda which goes back to the precipitation process.
calcination

- The separated aluminum hydroxide is washed to remove residues of caustic soda and is heated to drive off excess water in long rotating kilns called “calciners”.

\[ 2\text{Al(OH)}_3 \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\text{O} \]

- Aluminum oxide (alumina) emerges as a fine white powder that looks like granulated sugar but is hard enough to scratch glass. The widely-used abrasives corundum and emery are forms of alumina.

- Refined alumina consists of about equal weights of aluminum and oxygen, which must be separated in order to produce aluminum metal.
Alumina production - summary

Bauxite digestion:
- T: 170...180 °C
  - NaOH

Filtration:
- Na[Al(OH)₄]

Crystallization precipitation:
- Al(OH)₃
  - Seeding to facilitate precipitation

Red mud

Aluminium oxide

Rotary kiln calcination
Production of Alumina - summary

- Immersing crushed bauxite into a caustic soda solution which dissolves the alumina to form sodium aluminate liquor.
- After filtering, the impurities are left behind as a "red mud" and the liquid is treated to precipitate the aluminium content out of the solution which is now in the form of aluminium hydroxide.
- This material is then separated from the liquor and changed to alumina, which resembles course granulated sugar, by heating in kilns at 1000 °C.
- Approximately 4 kilogrammes of bauxite is required to produce 2 kilogrammes of alumina.
Production of alumina

In 2010, 87.4 mil tonnes of alumina were produced world-wide. Alumina refineries are often located near to bauxite mines for logistics reasons.

QAL Alumina plants
Queensland
Australia
Production of alumina

Rusal Aluminium (Ireland) works: 1.800.000 ton/year alumina production capacity. One of the most modern plants in Europe.
Production of alumina

ETİ ALUMINIUM Seydişehir: processes 400,000 ton bauxite!
Red mud is generated at the rate of 77 million tons/year and is thus a major concern for aluminium industry.
Primary production

alumina

> A commodity product

> The raw material of the Hall-Heroult electrolysis process to produce aluminium

> Also a speciality chemical:
  - spark plugs
  - fire retardant
  - synthetic marble
  - catalyst
  - tooth paste
  - alun, aluminium fluoride
  - ceramic
  - refractory
Primary production

Alumina Typical Composition

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Wt.% (as metallic oxide)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Al}_2\text{O}_3$ (by diff.)</td>
<td>99.3-99.7</td>
</tr>
<tr>
<td>$\text{Na}_2\text{O}$</td>
<td>0.30-0.50</td>
</tr>
<tr>
<td>$\text{SiO}_2$</td>
<td>0.005-0.025</td>
</tr>
<tr>
<td>$\text{CaO}$</td>
<td>&lt;0.005-0.040</td>
</tr>
<tr>
<td>$\text{Fe}_2\text{O}_3$</td>
<td>0.005-0.020</td>
</tr>
<tr>
<td>$\text{TiO}_2$</td>
<td>0.001-0.008</td>
</tr>
<tr>
<td>$\text{ZnO}$</td>
<td>&lt;0.001-0.010</td>
</tr>
<tr>
<td>$\text{P}_2\text{O}_5$</td>
<td>&lt;0.0001-0.0015</td>
</tr>
<tr>
<td>$\text{Ga}_2\text{O}_3$</td>
<td>&lt;0.005-0.015</td>
</tr>
<tr>
<td>$\text{V}_2\text{O}_5$</td>
<td>&lt;0.001-0.003</td>
</tr>
<tr>
<td>$\text{SO}_3$</td>
<td>&lt; 0.05-0.20</td>
</tr>
</tbody>
</table>
Production of Al from Al\(_2\)O\(_3\)

Aluminum and oxygen form such a strong chemical bond that it takes a very large amount of energy to separate them by heating. Although Al as a pure metal melts at about 660°C; Al\(_2\)O\(_3\) requires a temperature of about 2015°C before it will melt. Chemical methods of breaking down aluminum oxide developed in the mid-19th century were so expensive that metallic Al cost as much as Ag. The small amounts of Al that were produced were used mainly for jewelry and other luxury items.
Production of Al from Al\textsubscript{2}O\textsubscript{3}

Early researchers thought of using electricity to separate aluminum from its oxide in solution but were frustrated by seemingly:
- high energy requirements;
- the inadequacy of their only source of electricity—batteries;
- and the insolubility of alumina in water.

The invention of the rotary electric generator, the dynamo, in 1866 solved part of that problem. However, that was not enough for economic production!
Production of Al from $\text{Al}_2\text{O}_3$

- The other part was solved in 1886 by Charles Martin Hall in the United States and Paul L.T. Heroult in France.

- Hall and Heroult found that alumina would dissolve in cryolite (a sodium aluminum fluoride salt- $\text{Na}_3\text{AlF}_6$) at about 950°C.

- Once dissolved, the aluminum oxide is readily separated into Al and O by electric current.

- Cryolite has the practical advantages of stability under process conditions and a density lower than that of aluminum, allowing the newly-forming metal to sink to the bottom of the reduction cell.”
Electrolysis

- Primary aluminium is produced in reduction plants (smelters), where pure Al is extracted from alumina by the Hall-Héroult process.
- The reduction of alumina into liquid Al is operated at around 950 °C in a cryolite bath under high intensity electrical current.
- This process takes place in electrolytic cells (or “pots”), where carbon cathodes form the bottom of the pot and act as the negative electrode.
- Anodes (positive electrodes) are held at the top of the pot and are consumed during the process when they react with the oxygen coming from the alumina.
Electrolysis

- Oxygen merges with the carbon used to line the cell and escapes in the form of carbon dioxide.
- Molten aluminium tapped from the pots is transported to the cast house where it is alloyed in holding furnaces by the addition of other metals (according to the users' needs), cleaned of oxides and gases, and then cast into ingots.
- These can take the form of extrusion billets, for extruded products, or rolling ingots, for rolled products, depending on the way it is to be further processed.
- Aluminium mould castings are produced by foundries which use this technique to manufacture shaped components.
Hall-Heroult Process

Electrochemical process to reduce alumina into aluminium
Alumina is dissolved in molten kryolite:
\[ \text{Na}_3\text{AlF}_6 + \text{Al}_2\text{O}_3 + \text{AlF}_3(-\text{excess}) + \text{CaF}_2 \]
\[ T = 960°\text{C} \]
\[ I = 200-240\text{kA} \]
\[ E \sim 4\text{V} \]
Hall-Heroult Process

Inner lining of each cell serves as the cathode. Anode is manufactured from carbon. Cathode lasts longer since it does not take part in the reaction.

- Solid crust of Electrolyte
- Graphite anodes
- a deep steel mold lined with carbon
- Al$_2$O$_3$ dissolved in molten cryolite
- Molten aluminium
- Molten aluminium
- Graphite cathode
- Insulator
Hall-Heroult Process

Reactions:
cathode: \(4 (\text{Al}^{3+} + 3e \rightarrow \text{Al}(l))\)
anode: \(3 (\text{C}(s) + 2\text{O}^{2-} \rightarrow \text{CO}_2(g) + 4e)\)
\(4\text{Al}^{3+} + 3\text{C}(s) + 6\text{O}^{2-} \rightarrow 4\text{Al}(l) + 3\text{CO}_2(g)\)
(2\text{Al}_2\text{O}_3 \text{ (cryolite)} + 3\text{C} \text{ (anode)} \rightarrow 4\text{Al}(\text{liq}) + 3\text{CO}_2 \text{ (g)})

Oxygen atoms, separated from aluminum oxide, carry a negative electrical charge and are attracted to the positive poles in each pot. These poles, or anodes, are made of carbon which immediately combines with the oxygen, forming the gases carbon dioxide and carbon monoxide.
Hall-Heroult Process

These gases bubble free of the melt, leaving behind the aluminum which collects at the bottom of the pot. The negative electric pole, or cathode, forms the inner lining of each pot. It is also made of carbon. As a cathode it does not react with the melt, so it has a long service life.

When sufficient molten aluminum has collected at the bottom of a pot, it is siphoned into a crucible for transport to alloying and casting facilities. The aluminum produced by the Hall-Heroult process is more than 99 percent pure.
Energy consumption is extremely high!

Hence, primary production plants are almost always located close to economic energy sources.

Some of these plants have access to energy via their own establishments!
Hall-Heroult Process
The Hall-Heroult process uses a lot of electricity but only a low voltage, so it is practical to connect many reduction cells, or “pots”, in series along one long electrical circuit, forming a “potline.”

Modern cells are operated with currents of around 250,000 amperes but at only four or five volts each.

Such cells use about six or seven kilowatts of electricity per pound of aluminum produced.

The heat generated by electrical resistance keeps the solution molten.
Hall-Heroult Process

- The process, therefore, steadily consumes the carbon anodes, which must be renewed either by regular replacement or by continuous feeding of a self baking paste (Soderberg anode).

- About 225 g of carbon is consumed for every 455 g of aluminum produced.

- Most aluminum reduction plants include their own facilities to manufacture carbon anodes, each of which may weigh 270 - 320 kg and must be replaced after about 14 days of service.
anodes

- There are two types of anodes currently in use.
- All potlines built since the early 1970s use the prebake anode technology, where the anodes, manufactured from a mixture of petroleum coke and coal tar pitch (acting as a binder), are pre-baked in separate anode plants.
- In the Soederberg technology, the carbonaceous mixture is fed directly into the top part of the pot, where self-baking anodes are produced using the heat released by the electrolytic process.
entire production cycle

**Chemical processes**

- **Bauxite**
- **Crusher**
- **Filter**
- **NaOH**
- **“Digester”**
- **Red mud**
- **Al₂O₃·3H₂O**
- **Al₂O₃**
- **AlF₃**
- **Na₃AlF₆**
- **Molten electrolyte**
- **Molten aluminium**
- **Syphon**
- **Crucible**
- **Holding furnace**
- **Aluminium ingot**

**Electrolytic process**
Steps of aluminium production

Alumina production

- 4 kg bauxite
- 2 kg alumina ($\text{Al}_2\text{O}_3$)

Melting

- 2 kg $\text{Al}_2\text{O}_3$
- Carbon anode
- Cryolite bath
- Steel pot

Alloying and casting

- 1 kg Al
- Gas scrubber
- Ingot
- Billet
- Rolling slab
Aluminium production

The world production of primary aluminium reached about 44 million tonnes in 2011. The average annual production growth over the last 20 years has been 3-4%. China is by far the largest producer, and also has the highest growth rate. The Gulf region also has a significant growth, while production in most other areas either has declined or been stagnant in recent years.
Aluminium output has increased by a factor of 13 since 1950, making aluminium the most widely used non-ferrous metal.

In 2010, the world-wide production of primary aluminium was about 42.6 million tonnes per year for installed capacity of 53.6 million tonnes. Very recently China developed its aluminium production very rapidly, and it is the biggest producer in the world with over 17 million tonnes of production.

In Europe the main producing countries are Germany, France, Spain, Norway and Iceland. World-wide, production plants are mainly located where suitable electrical energy resources are available.
aluminium production

### History of primary aluminium production

**Main producing countries and regions 1950-2012**

1950's - use in construction sector
1970's - use in cans
1973, 1982 - oil crisis
1981-1986 - Japanese production relocates
1990's - use in cars
1990-1993 - Soviet break-up
1993-2007 - the emergence of China
2008-2009 Global crisis

Source: EAA, AA, JAA, ABAL, RTA, Metallstatistik
Aluminium production

- China: 45%
- Others: 6%
- Europe: 9%
- CIS: 10%
- USA: 4%
- Canada: 6%
- Oceania: 5%
- Brazil: 3%
- Middle East: 8%
- India: 4%
Aluminium production in EU

Aluminium Sector in Europe*, 2011

TOTAL = PRODUCTION + Net IMPORTS

- **BAUXITE**: 15.5 Mt, 6 plants
  - **ALUMINA**: 10.8 Mt, 12 plants
    - **METAL**: 13.2 Mt, 31 plants
      - **SEMI’S**: 55 plants
        - **ROLLED**: ±4.5 Mt (38%)
        - **EXTRUDED**: ±3.0 Mt (25%)
        - **CASTINGS**: ±3.2 Mt (27%)
        - **Wire, powder, slugs**: ±1.2 Mt (10%)

* Europe: Former CIS excluded, except Baltic states, Turkey included
1 Based on statistics (includes recycling from tolled and purchased scrap)
2 Integrated automotive producers incl.
Aluminium production in Turkey (tons)

Extrusion, ingot, rolled, foil, conductors, others
Aluminium imports in Turkey (Tons)

Aluminium ingots is the most imported item!
Aluminium use

- Castings: 23.1%
- Extrusions: 29.3%
- Rolled products: 41.5%
- Wire/cable: 6.1%
- Others: 6.1%
Aluminium use

<table>
<thead>
<tr>
<th>Aluminium use</th>
<th>(%)</th>
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<tbody>
<tr>
<td>construction</td>
<td>25</td>
</tr>
<tr>
<td>transport</td>
<td>24</td>
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<tr>
<td>packaging</td>
<td>15</td>
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<tr>
<td>Electric/electronic</td>
<td>10</td>
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<tr>
<td>General engineering</td>
<td>9</td>
</tr>
<tr>
<td>furniture/office items</td>
<td>6</td>
</tr>
<tr>
<td>Iron &amp; steel, metallurgy</td>
<td>3</td>
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<tr>
<td>Chemical and agriculture industries</td>
<td>1</td>
</tr>
<tr>
<td>others</td>
<td>7</td>
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</table>
Aluminium industry in Turkey
Aluminium industry in Turkey

Primary aluminium production: Eti Alüminyum A.Ş.
per year 461.000 ton bauxite/
200.000 ton alumina /
60.000 ton molten aluminium

Number of companies >1500
employment >30000
Production capacity ~750.000 ton
consumption:
  2006  446.000 ton
  2007  526.000 ton
  2008  556.000 ton
Per person ~ 9 kg
AB ~ 30kg
turnover : 4 billion US Dolar
**Aluminium production in Turkey (1000 ton)**

<table>
<thead>
<tr>
<th>Üretim</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>Değişim (%)</th>
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<tbody>
<tr>
<td>Birincil Alüminyum</td>
<td>60,0</td>
<td>60,0</td>
<td>63,4</td>
<td>61,2</td>
<td>30,0</td>
<td>54,0</td>
<td>56,0</td>
<td>3,7</td>
</tr>
<tr>
<td>İkincil Alüminyum</td>
<td>65,0</td>
<td>70,0</td>
<td>80,0</td>
<td>94,0</td>
<td>120,0</td>
<td>150,0</td>
<td>265,0</td>
<td>10,0</td>
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<tr>
<td>Ekstrüzyon</td>
<td>190,0</td>
<td>215,0</td>
<td>235,0</td>
<td>265,0</td>
<td>230,0</td>
<td>275,0</td>
<td>290,0</td>
<td>5,5</td>
</tr>
<tr>
<td>Yassı (Levha, rulo)</td>
<td>128,1</td>
<td>125,4</td>
<td>146,0</td>
<td>140,6</td>
<td>135,2</td>
<td>198,0</td>
<td>224,0</td>
<td>13,1</td>
</tr>
<tr>
<td>Folyo</td>
<td>31,4</td>
<td>34,7</td>
<td>39,5</td>
<td>43,4</td>
<td>50,7</td>
<td>60,0</td>
<td>65,0</td>
<td>8,3</td>
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<tr>
<td>İletken</td>
<td>30,0</td>
<td>33,0</td>
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<td>33,2</td>
<td>50,0</td>
<td>70,0</td>
<td>85,0</td>
<td>21,4</td>
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<tr>
<td>Diğer</td>
<td>52,8</td>
<td>56,5</td>
<td>59,8</td>
<td>63,3</td>
<td>55,0</td>
<td>-</td>
<td>62,0</td>
<td>6,9</td>
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</table>

Kaynak: TALSAD
Foreign trade in Turkey (billion US Dollars)

<table>
<thead>
<tr>
<th>Year</th>
<th>ihracat</th>
<th>ithalat</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>2006</td>
<td>1.2</td>
<td>1.8</td>
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<tr>
<td>2007</td>
<td>1.6</td>
<td>2.4</td>
</tr>
<tr>
<td>2008</td>
<td>1.8</td>
<td>2.5</td>
</tr>
<tr>
<td>2009</td>
<td>1.4</td>
<td>1.6</td>
</tr>
<tr>
<td>2010</td>
<td>1.92</td>
<td>2.49</td>
</tr>
<tr>
<td>2011</td>
<td>2.3</td>
<td>3.3</td>
</tr>
</tbody>
</table>
See you next week!
Melting aluminium

Aluminium ingot (primary production)

Returns/chips/scrap recycling

Melting furnace

Technological melt treatments

- mixing/homogenization
- fluxing
- gas + inclusion removal
- drossing + filtration
- alloying
Melting aluminium

- Aluminium foundries are advised to operate separate melting and holding furnaces.
- The melting furnace is used to melt ingots, scrap and returns.
- The holding furnace is used to maintain the molten alloy transferred from the melting furnace at the casting temperature with a uniform chemistry.
- Only final and minor adjustments are made at the holding furnace.
- Fuel oil and natural gas are employed for melting furnaces, electric energy for holding furnaces.
- The former is cheaper but electricity offers higher quality.
Melting aluminium

Energy required to melt 1 kg aluminium (kJ)

Temperature (°C)
Melting aluminium

To bring the temperature of the charge to the melting point: %58

To melt the charge: %34

To heat the liquid aluminium to the casting temperature: %8

Energy required to cast 1 ton aluminium (kwh)

Temperature (°C)

Anteil Wärmbedarf bezogen auf 760°C in %
Reverbatory furnaces

energy: fuel oil, natural gas!

Burners are mounted on the furnace walls.

Heat transfer: radiation from the furnace walls + convective heat transfer from the burners

capacities <150 ton! / relatively low capital cost
Reverberatory furnaces have gas or oil burners firing within a refractory hood above the metal bath. The burner flame is deflected from the roof onto the hearth. They are used as batch melters. They are simple and have relatively low capital cost which makes them attractive for bulk melting of ingots and foundry returns.
reverbatory furnaces

- They are produced in a variety of configurations such as fixed or tilting, rectangular or cylindrical with melting capacities from 200 to 1300 kg/hr.
- Large reverberatory furnaces give rapid melting and can handle bulky charge material, but the direct contact between flame and charge may lead to high metal losses, gas pick-up and considerable oxide contamination.
- Temperature control can also be difficult.
- This type of furnace is being used less because of its relatively low thermal efficiency of around 1100 kWh/tonne.
Reverberatory furnaces
Reverbatory furnaces

Melting efficiencies typically 15%-39%
Efficiency may be up by ~ 10%-15% via recuperation.
Reverberatory furnaces

**Advantages:**
Capacity: high volume melting
Operation and maintainence costs are low!

**Disadvantages:**
Excessive melt loss due to oxidation
increased contamination and inclusions
increased dross %3-7
low thermal efficiency ~%25
larger space required!
More hydrogen gas
Fluctuations in melt temperature +/- 50º C
Reverberatory furnaces

Heat loss from exhausts (%35-50)

Heat loss from walls (%1-7)

Incomplete combustion heat loss (%0-25)

Useful heat output (%10-40)

Air, gaseous fuel, oxygen, burner, furnace, load

Diagram showing the components and heat losses in a reverberatory furnace.
Electric reverberatory furnaces

Hardly ever used for melting!
Employed as a holding furnace.
Refractory lined furnaces which rely on resistance heating elements mounted often at the ceiling and on the walls for heating.
Electric reverbatory furnaces

Used for melting low volumes when emissions control, metal quality and melting efficiency are critical.

**Advantages:**
- low exhaust emissions!
- low melt loss due to oxidation!
- less furnace cleaning

**Disadvantages:**
- high energy cost!
- low production capacity and production rate!
- high investment cost!
- heating elements frequently replaced!
Crucible furnaces

Crucible furnaces are widely used as melters, melter/holders and holders. Crucible furnaces are:

- simple and robust
- widely available in a range of sizes
- either fixed or tilting
- suitable for heating by different fuels
- capable of low melting losses
- relatively inexpensive

Alloy changes are readily carried out and both degassing and metal treatment can be done in the crucible before it is removed for casting.
Crucible furnaces fall into three main types:

- **Lift-out** The crucible is removed from the furnace for pouring
- **Tilting** The furnace body containing the crucible is tilted to pour the molten metal
- **Bale-out** The molten metal is ladled out
crucible furnaces/fuel oil-natural gas
Crucible furnaces
fuel oil-natural gas

Indirect heating (crucible is heated to heat the load!)
Suitable for melting small (<500 kg) quantities

**Advantages:**
- alloy can be changed easily!
- maintainence costs are low!
- investment cost is low!
- small space required!

**Disadvantages:**
- efficiency very low (falls down to %12!)
- excessive emissions!
- size limitations!
Crucible furnaces
fuel oil-natural gas

exhaust

Exhaust gases

burner

crucible
Crucible furnaces/electric

- Similar to gas fired crucible furnaces.
- Crucible is heated with resistance elements.
- Capacity is limited.
- Preferred when alloy change is needed frequently.

Advantages:
- low emissions!
- low oxidation loss!

Disadvantages:
- high energy costs
- size limitations
Crucible furnaces/ electric

Surface of aluminium melt is clean and shiny: evidences clean melting conditions
Gas vs electric crucible furnaces

Molten aluminium is highly reactive, it instantly reacts with the water vapor which is present in all products of combustion according to the following equation:

$$2 \text{Al} + 3 \text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 + 3 \text{H}_2$$

$\text{Al}_2\text{O}_3$ produces hard spots in castings.
Gas vs electric crucible furnaces

H₂ gas is highly soluble in molten aluminium and completely insoluble in solid aluminium, appearing as porosity in finished castings which can produce surface roughness, casting fractures, leaky castings, unsealable machined surfaces, etc.

PRODUCTS OF COMBUSTION LEAK THROUGH CRUCIBLE GASKET TO REACT WITH MOLTEN ALUMINUM
gas-fired vs electric resistance crucible furnace

Primary A356 aluminum alloy melted in silicon carbide crucibles in gas-fired and electric resistance furnaces, brought to the same pouring temperature, degassed with ultra dry nitrogen, skimmed, and poured into green sand molds and permanent molds. Hundreds of test bar samples cast, test bars pulled, and the results recorded, plotted, and subjected to statistical analysis.

The results were profound: Tensile strength, yield strength and elongation properties were almost uniformly superior in the electrically melted samples regardless of the type of molds used.
The mechanical properties of test bars melted in the gas-fired furnace reached only 80% of the mean values of electrically melted test bars. The mechanical properties of the electrically melted castings, were much more uniform and consistent. The electrically melted test bar samples demonstrated mechanical properties that were much more consistent and tightly grouped while the natural gas melted test bars had a much wider variation in mechanical properties. Some natural gas melted test bars tested significantly below the red curve mean.
gas-fired vs electric resistance crucible furnace
gas-fired vs electric resistance crucible furnace

The natural gas melted test bars almost invariably broke at a dross inclusion, a hydrogen gas bubble, or even just a thin film of aluminium oxide, while the electrically melted test bars rarely showed any dross, oxide or hydrogen porosity at the breaks.
Leakage of Combustion Products

- The molten aluminium in the gas-fired furnace is not isolated from the furnace’s combustion chamber at all.
- This is because the sealing gasket between the top of the crucible and the underside of the steel furnace cover is made of compressible fibre insulation to allow the crucible to expand without cracking.
- Because of the positive pressure in the combustion chamber and the porous fiber gasket, combustion gasses freely penetrate the gasket, immediately coming into contact with the surface of the metal bath.
gas-fired vs electric resistance crucible furnace

- With the electric furnace, the relative humidity is always the same inside and outside.
- But with the gas-fired furnace, even though there is a flue that pipes most of the combustion gases outside, the relative humidity inside the foundry is always significantly higher.
- This means, in addition to the combustion gases that are penetrating the crucible gasket, there is additional water vapour present in the air that is coming from various leaks in the burners, refractories, flue pipes, etc. which can react with the molten aluminium.