THE METAL HINGES OF WESTERN HISTORY

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INTRODUCTION

Is it not true that the picture we have of human history too often looks like a highway through time consisting of a linear succession of periods of peace and hardships, of victories and devastating failures? Is the attention not too exclusively drawn to the role of kings and warlords, to political systems and religions, to clashes between peoples and nations and to the resulting peace treaties?
The role of technology and technological development in the shaping of the pilgrimage of humanity is often overlooked.
This is especially the case when we consider the very important role played by metallurgy and the processing of metallic materials.

This deficiency can most probably be attributed to the silent paths, the hidden and long hiking trails of human adventure along which technological developments take place, side-tracked from the history highway mentioned above. From the dawn of time till today, these trails pass along places evolving from small village and farm craft centres in the first human settlements, over hidden military and civil workshops in antique cities, through kitchen-size labs in palaces, castles and convents into the inconspicuous places of university, public or industrial research centres of today. In spite of the humbleness of the hiking trail of metals history, curiosity, creativity and craftsmanship –nowadays called "the innovation genes"– have made that class of materials to be the most influential one in history, from the early Neolithicum of 10000 B.C. till the midst of the 20th century[1]!
Indeed, from time to time, the long hiking trails of metallurgical development crossed the highway of political and societal history. It will be

[1] Mike Ashby in "Materials selection in Mechanical Design", Pergamom Press, Oxford 1992

shown by several examples how a new metal or alloy, a new elaborating or working process then fundamentally influenced the wealth of peoples, the outcome of wars, shifted the gravity centres of economic welfare and cultural development. These were the metal hinges along the history of humanity.

THE CHALCOLITHIC HINGE

Metals consist of numerous crystals –called "grains"–, with much simpler crystal structures than stone (silicate a.o.) materials. Some of their atomic planes are densely stacked allowing them to glide over each other like a stack of playing cards. Small stresses can already induce such a glide, since a glide corresponds to the movement of numerous dislocation faults, comparable to the displacement or "glide" of a worm by moving contractions along its length. This is the mechanism of plastic deformation.
During plastic deformation by forging, hammering, etc... the number of "dislocations" increases strongly, up to the point that dislocations on one plane start to hinder the movement of dislocations on other planes. Hence, the flow stress increases, a mechanism which is called "strain hardening". And as a result, metals gain strength by plastic deformation.
Consequently, further deformation becomes more difficult: the second hammer blow needs a greater force than the first one, the third one is even more difficult than the second one... However, by annealing at a sufficiently high temperature (e.g. 600° for copper), the metal can be softened again; it recrystallises into an assembly of completely new grains and the majority of dislocations is annihilated; the "dislocation forest" is cleared so that the original state with low dislocation density is restored; plastic deformation can therefore be continued.

Native copper, like native gold and silver, was known from Palaeolithic times. Even if the red metal was less rare than its more noble native sisters, gold and silver, the regular copper nodule findings in the alluvial basins in the Balkan and the Middle East were not so abundant as to allow its systematic use as a tool material. This explains why this wonderful malleable material was mainly used for ceremonial objects, ornaments and decorations. Nevertheless, although the technology was rather simple –the natural occurring metal did not require smelting or even melting–, we can expect that our far ancestors realised that a couple of blows with a stone hammer strengthened the copper and that property was certainly exploited from time to time to make one or the other tool. They also found out that annealing a cold hammered piece of copper restored its workability and this allowed them to create ornaments of complex geometry, which were highly valued.

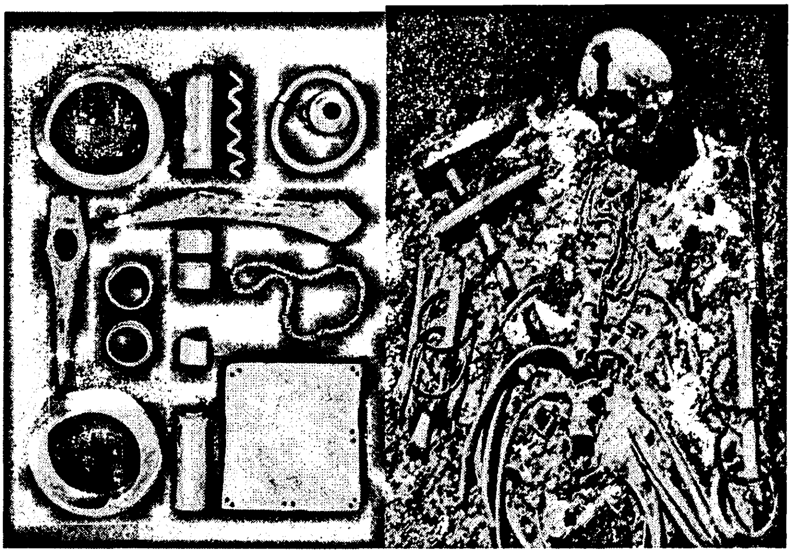

Fig. 1 : Reconstruction of the Varna necropolis tomb nr 4, which most probably belonged to a warlord. He was buried with several golden ornaments and copper axes.[2] *The copper most probably was mined in a nearby quarry*

Theories about where and how the first copper *smelting* technology was developed are still highly speculative. The curiosity of potters being awakened by the regular observation of solidified red copper drops on the walls of pottery ovens when e.g. greenish malachite or blue azurite had been added to the clay in order to colour the vessels, is in many places the most plausible cradle of copper metallurgy. It only needed a –for potters exceptionally high– temperature of 1083°C, sufficient air blow and close contact with the charcoal, in order to transform the copper carbonate –in the case of malachite– into copper oxide, to decompose that oxide and to liquefy the thus obtained copper. Creative and entrepreneurial Neolithic craftsmen then detected which minerals contained the highest copper concentration, and started to "diversify" their pottery shop with a copper smelting one.

[2] "guide de la préhistoire de Varna"– ed. Archeologisch museum Varna

In the 5th millennium BC, copper-containing mineral deposits were mined in several places. Archaeological evidence of an established trade of colourful minerals amongst Middle Eastern and South-East Asian countries equally exists. This explains why Rutna Glava in Serbia, Varna in Bulgaria (fig. 1), as well as several places in Turquie, Northern Iran and Iraq, and recently also in Corsica and Sardinia[3],[4], all claim to have the historically eldest copper mines and smelting shops.

At the end of the third millennium BC, in Timna, in the southern Negev desert, 30 km north of Eilat, and in several Ouadis between the Nile and the Red Sea, there already existed a well-structured copper mining and copper transformation industry. Smelting took place close to the mines, whereas casting in open one-faced moulds, forging, tooling and tool maintenance shops were found close to the farming regions and in the neighbourhood of the great civil engineering constructions of Pharaonic times. The Egyptians had improved the –imported– copper metallurgy, by adding iron-ore reacting with quartz to form a fayalite slag, thus improving the soundness of the copper metal, from which they made e.g. hammered and polished razors and mirrors[5], needles and knives, chisels and axe heads. In a later stage, when the surface oxide ores were near to exhaustion, they developed the roasting technique which allowed them to extract the metal from underground sulphide ores –like chalcopyrite $CuFeS_2$ - by first transforming the copper sulphide into copper oxide.

The development of copper metallurgy by itself did not have such an important impact on the daily life of people. It did not raise the technological stakes high enough to inaugurate an independent "copper age". The reasons are clear: though the malleability of copper already led to the development of a new set of ornaments, tools and weapons, the Neolithic people were faced with the limitation that as-cast copper is only 200 MPa strong and cold hammered tools barely reach a strength of 400 MPa, which is still far below that of flint and obsidian. Moreover, being a pure metal, the danger of having

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[3] G. Camps "Préhistoire d'une île". Origine de la Corse. Errance. Paris 1988; quoted by J. Briard in "l'Age du Bronze en Europe" [30]

[4] The isle of Cyprus, that was rich in copper and even gave its name to the red metal, does not seem to claim to have the eldest copper mines.

[5] The eldest known copper mirrors stem from the Ancient Empire (around 3000 BC).

entrapped air and gases in the as-cast copper objects[6], seriously deteriorating their properties, always exists.
Therefore, the old stone tools still did the most important jobs. The "lithic" part of the chalcolithic era remained the central element.
The "chalco" part, on the other hand, did have a significant contribution since copper metallurgy definitively opened the metal era. Turning a hard rock into a soft and useful material, which could be cast and recast into a variety of objects with complex geometry, which could be plastically forged and formed into the most beautiful implements, was a unique and irreversible step in human development.

TOOL DIVERSITY AND DEVELOPMENT OF THE HUMAN MIND

Today, when we look at the diversity of metallic objects and structures, which are made by human hands to cope with the physical world, to facilitate social intercourse, to delight our fancy and to create symbols of meaning, we have to conclude that their number supersedes the number of species of flora and fauna created by the natural evolutionary process[7].

The meaning of this diversity is, however, more than just a quantitative one. At the entrance of the "*Musée de l'outil et de la pensée ouvrière*" in Troyes, France, we read a text of the Jesuit father Paul Feller, saying *« l'ouvrage du métier, ne serait-il l'agent du développement de la pensée? »* [8].
What did father Keeler mean?

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[6] Indeed, pure metals have a specific melting point (1084°C in the case of copper). When objects with a complex geometry or different wall thicknesses are cast, the cooling rate can differ from one place to another. As a result, air can be entrapped in so-called "shrink holes" and gases escaping from the solidifying metal can form "blowholes".
[7] George Basalla in "The evolution of technology" – Cambridge History of Science Series – Cambridge University Press 1988
[8] The "Musée de l'outil et de la pensée ouvrière"in Troyes has a collection of many thousands of tools, nicely arranged first according to the nature of the tool (hammers, files, saws, chisels, axes, tongs...) and secondly according to the craft where they are used (smiths, locksmiths, tanners, bricklayers, mechanics, shoemakers, roofers…). The museum also contains a library with more than 30.000 works most of them related to various crafts, but also many books about the history of technology, a.o. a 1572 translation of Vitruvius and an original edition of *l'Encyclopédie* of Diderot et d'Alembert.

When at the end of the last glacial period, humans gradually left a life of hunter-gatherer and started to work the uncovered land, to grow crops and to domesticate animals, the need for appropriate domestic and agricultural tools led to the creation of workshops in the first human settlements. The small variety of stone tools for hunting, for cutting meat into pieces and for transforming animal skin into clothing did not meet the new needs for house building and farming anymore. Settling also stimulated the desire for decoration of houses and diversifying personal dressing-up and last but not least led to more sophisticated religious worship and burial cults.
The arts of felting, spinning and weaving fibres into textiles were developed. The already known art of making ceramic votive figurines from clay was extended and expanded into the art of pottery because food, oil and water now could be stored at home instead of constantly having to be transported in small and light leather bags. And, as already mentioned, out of the art of pottery arose the art of transforming by fire natural raw substance into a new and useful material. A material that, unlike stone tools, could be shaped into the greatest variety of tools and implements, dedicated for every kind of human activity.

From then on, at increasing pace, the pressure of always having to find new solutions for new needs, reinforced by the existential pleasures of creating new processes and new metallic tools, doubtless broadened and deepened people's world of technical thinking. Keelers' words: "l'ouvrage du métier, serait-t-il agent du développement de la pensée." simply mean: "Did tool workshops not accelerate the development of the human mind?"[9].
Unfortunately, that liberation of human imagination not only provided the springboard for almost all progress towards civilisation. All along history it was confirmed that this liberation did not necessarily improve human nature; the development of new materials and tool-making processes simultaneously opened doors for the development of always more destructive devices, an evolution which is erroneously also often presented as "progress". A German poster (fig. 2) that appeared during the First World War expressively

[9] In a mood of cultural optimism, we can attach a similar meaning to the variety of applications developed within the information and communication technology of today.

illustrates this inevitable double face of progress: "Pflug und Waffen, helft Ihr uns schaffen"[10]

fig. 2 : "Pflug und Waffen , helft Ihr uns Schaffen"[10]

NOBLE METAL HINGES IN ANTIQUITY

Egypt was not only a present of the Nile, but also of the Nubian gold

As mentioned, by about 5000 BC men succeeded to smelt copper from gossans formed from oxidized complex ores. Since the melting point of gold (1064°C) is about the same as that of copper (1084°C), it can be reasonably concluded that gold metallurgy –melting and remelting- was developed during the same period, as is illustrated by the joint presence of artefacts of both metals in 4th millennium BC tombs e.g. in Varna, Bulgary (fig.1).
Later on in Egypt, from the early Pharaonic times till the end of the Middle Kingdom, gold mining was an established activity in the desert valleys to the east of the Nile. But the gold reserves were not endless and close to the start of the Middle Kingdom (1550 BC) depletion came in sight. Fortunately, the first rulers of the New Kingdom closed an important alliance with Nubia.

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[10] "Plakate aus dem ersten Weltkrieg" Österreichische Nationalbibliothek, reg.nr. 21537-Dia7, translation: Ploughs and weapons help us to create

This stimulated their metallurgists to develop a process, enabling the extraction of gold from the native "elektrum", a natural gold-silver[11] alloy discovered in Nubia. They sprayed common salt solution on the molten material, thus removing the silver from the melt in the form of gaseous silver-chloride, leaving a bath of nearly pure gold metal[12].

This technology has substantially contributed to the wealth and economic power of the New Kingdom[13]. Alluvial auriferous sand was treated in Nubia[14] (from placer deposits) as well as nuggets from the mines (from "lode" deposits). The latter was called nub-en-set, i.e. 'gold of the mountain', while alluvial gold was named nub-en-mu, i.e. 'gold of the river'. In both cases the noble metal particles obtained were welded together by hammering them into a lump of gold that was subsequently molten, refined and cast into a semi-finished shape.

Archaeologists mention that the gold mines in Nubia and other parts of the Egyptian empire were very efficiently designed and controlled. Although this statement might be true, we should complement it by pointing out the profound disregard for the numerous slaves who were working in the mines. Without that workforce the Egyptian Kingdom would not have lasted so long.

The Lydian Lion: from Barter Trade into Monetary Trade

Elektrum is believed to be the first metallic material from which coins were made. This happened around 650 BC in Lydia under the reign of king Gyges. Elektrum was collected in Sardis from the washings of the Pactolus river. It was in fact much better for coinage than gold mostly because it was harder and more durable. Moreover, techniques for separating gold from elektrum were not widespread in Lydia at that time.

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[11] Elektrum contains between 20 and 30 wt % silver

[12] Accord. to Paul Craddock – British Museum – Journal of Metals Feb. 2001 – the Egyptian gold had a purity between 17 and 23 carad.

[13] Considering that the Egyptian word for gold is nub, the origin of the name Nubia becomes clear.

[14] Auriferous sand was placed in a bag made of a fleece with the woolly side inwards; water was then added and two men vigorously shook the bag. By pouring off the water, the earthy particles were carried away, leaving the heavier particles of gold to adhere to the fleece. This technique does not differ substantially from the one used during the gold rush in 19th century America.

One of the oldest known coins is the "Lydian Lion", shown in fig.3.

Fig. 3: The coin illustrated above is a Lydian third slater, or trite, minted sometime around 600 BC in Lydia[15]

There was, however, one problem. The great variety in elektrum compositions led to a variety in the real metal value of the coins since only the weight of the coin (14 g of elektrum was made into one 'slater' or around one month's pay for a soldier, and smaller fraction coins –e.g. trites– were also produced) and not the exact gold content of the coin was taken into consideration. For this reason, the expansion of monetary payment was slowed down[16]. This however changed rapidly when in Ancient Greece the first pure silver coins came into use.

The Lydian Lion is one extremely important hinge in our history, as it moved societies from barter trade into a much more practical monetary trade. The Lydian coins directly preceded ancient Greek coinage, which through Rome lies at the origin of all Western coinage, and through the Seleukids and Parthians, inspired all Islamic coinage[9-17].

How silver saved Europe

The further eventful role of precious metals in coinage will not be discussed here. Very often, the choice of metal –gold, silver, copper...– and alloy

[15] S. Karwiese in "The Artemisium Coin Hoard and the First Coins of Ephesus" Revue Belge de numismatique 137 (1991) p.8

[16] "Ancient coins of Lydia" http://www.snible.org/coins/hn/lydia.html

[17] The possible independent introduction of coinage in India and China is still under discussion

composition was closely linked to economic and political trends and turmoil. Its history has been described in numerous numismatic books.
There is however, one very important event in classical Greece, linked to a particular noble metal, which has had a crucial effect on the history of Europe.

It is known that by about 3000 B.C., people in Asia Minor and Crete had learned to smelt silver-lead oxide ores. But the first sophisticated processing of that ore, which allowed the extraction of silver, has been attributed to the Chaldeans in about 2500 B.C. They used a "cupellation" process to win the noble metal from the complex ores[18]. The need for silver (particularly for the flourishing Minoan and later Mycenaean civilisations) resulted in the location and exploitation of lead-silver deposits in what is now Armenia.

After the catastrophic destruction of the Minoan (Cretan) civilisation in 1600 B.C. and the decline of the Mycenaean culture around 1200 B.C., the centre of silver production moved to the mines of Laurion (near Athens), which provided silver for the burgeoning Greek civilisation and significantly expanded the silver trade throughout Asia Minor and North Africa after the 8th century B.C.

The Laurion mines were highly productive. The silver content of the ore was about 1500 gram per tonne[19]. For about 1000 years ending around the 1st century A.C., the Laurion mines were the largest individual source of world silver production (the process is described in fig. 4). But, –remember what was written about the Egyptian gold mines –, we should not forget that at the top of its production (600 B.C. to 300 B.C.), more than 20000 slaves were working in the mines, unfortunates condemned to labour amid the dust and pollution, so that the "democracy" could be rich.

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[18] After smelting in a charcoal furnace, and tapping off the slag, the silver-rich lead is treated in a "cupola", by directing a strong air jet on the surface of the bath. The lead is oxidized, forming a litharge (a lead-oxide dross) at the surface. Porous bone and tile fragments, leaving the silver behind, absorb this dross. This technique is called "cupellation".
[19] Robert Tylecote in "A history of Metallurgy" The Metals Society London 1992

Themistocles (525-460 B.C.) was a leader in that Athenian democracy during the Persian Wars[20]. He may have been fighting with his tribe in the victorious battle of Marathon (490) against Darius and it is told that he deeply envied the glory which Miltiades, the Marathon hero, earned.
At all events, the death of Miltiades left the stage to Themistocles and his main opponent Aristeides. Aristeides belonged to the established educated aristocracy of Athens and was highly esteemed for his honesty and virtue. Themistocles, on the other hand, had a rather obscure education, was notorious for pocketing bribes at any opportunity, but displayed a marked power of analysing a complex situation together with a genius for rapid action.

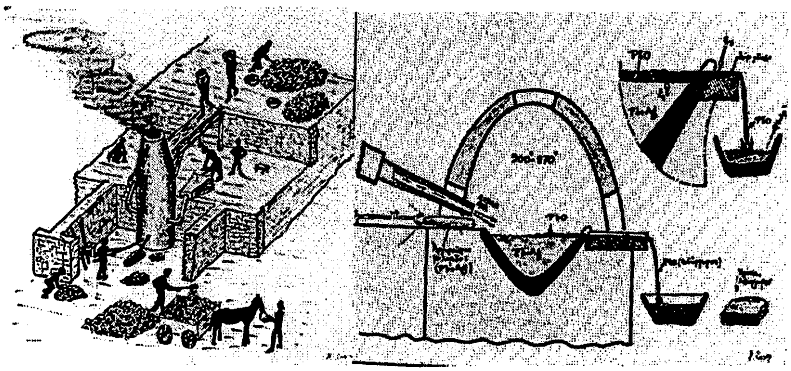

Fig. 4[21]: Work organisation around a lead ore smelting furnace. The furnace is loaded with ore and charcoal from a platform. Air is being pumped through from below. At the lowest level, the molten metal is tapped from the furnace outlet nozzle and transported to the cupellation furnace. The solidified slag is also carried off.
Detailed picture of the cupellation process with overflowing litharge. Sometimes the litharge was also removed by dipping iron rods, chilled in water, into the bath surface and letting the litharge congeal and adhere around the cool tip of the rod. The lead recovered from the litharge was mainly used in civil engineering constructions, e.g. for sealing stone pillars to their sockets.

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20 "Persian Fire- The first World Empire and the Battle for the West" – Tom Holland – Little,Brown –TimeWarner Book Group UK - 2005
21 Proceed. "Ancient Technology" – Finnish Institute of Athens – 1987 –ed. Tekniikan Museo Helsinki 1990

Themistocles favoured the expansion of the navy to meet a new Persian threat . He tried to persuade the Athenians to spend the surplus generated by a recently discovered, highly productive silver lode in Laurion, on building such a navy. Aristeides objected, defending the custom to divide the surplus income of the mines among the Athenian people. After months of discussion, now realising that a renewed Persian invasion loomed large at the horizon, the Athenians understood that it was of the highest importance to Athens and to the whole of Greece to accept the proposal of Themistocles to extend their navy with two hundred ships into a total number of around 300 triremes (Greek battleships).

The rivalry between Aristeides and Themistocles terminated in 483 by the expulsion of Aristeides.
Immediately, agents loaded with Laurion silver were sent across the Aegean, buying timber wherever it was available. Themistocles finished the fortification of the natural harbour of Piraeus thereby offering a much better protection than the open harbour of Phalerum. Day and night, the noise of saws and hammers rang in the shipyards of Piraeus and numerous Athenian craftsmen, assisted by unskilled citizens were building the newly-designed triremes at the astonishing rate of two a week.

In order not to create rivalry amongst the Athenian navy admirals, Themistocles diplomatically gave the command of the fleet to Eurybiades, a man of Sparta –though the Greek fleet stayed nominally under control of the Athenian leader–. Hence, the year prior to the invasion of Xerxes, Themistocles was not only the most influential politician in Athens but also in the whole Peloponnesian League. Knowing that the Athenian people were aware of being at the gravest moment of peril in their history, he could persuade them to leave their city undefended for the Persian army and seek refuge in Piraeus. Then came the defeat of the Spartan army at the mountain passes of Thermopylae, followed by the indecisive battle of Artemisium. However, these misfortunes rather strengthened Themistocles' and the Athenians' resoluteness. By a seemingly treacherous message to Xerxes, Themistocles managed to let the Persion armada glide into the narrow straits of Salamis. There, on September 29, 480 B.C., the triremes of Greece inflicted a crushing defeat over the much larger Persian army.

The retirement of the Persians left the Athenians free to restore their ruined city. Athens thus became the finest trade centre in Greece, and induced many foreign businessmen to settle in the city. But what 's even more important :

in the century following the battle of Salamis, arose the great philosophers of classical Greece : Plato, Socrates, Aristoteles, ...

Therefore, after more than two millennia, we can still confirm with great persuasion that lead-silver metallurgy, and more in particular the Silver Mines of Laurion allowed the visionary Themistocles to defeat the mighty Persian invaders, thus saving the cradle of European civilisation[22].

METAL ALLOY AND MIXING HINGES

By deforming metals at ambient temperature, e.g. by hammering or forging, their strength is increased. As mentioned earlier, this is due to the increasing number of dislocations, which act as obstacles to further dislocation movement. Whenever traffic in the city increases, it becomes more difficult to cross the city.

But driving through the city, or gliding over crystal planes, can also be effectively hindered when other obstacles are thrown on the road: these obstacles can be stones or rocks on the road, and foreign atoms or second-phase particles on the slip planes of the metal crystals. As a result, metal alloys are always stronger than pure metals.

When the obstacles are formed by foreign atoms, the hardening effect is called solid solution hardening. It is a strengthening mechanism that prevails in the case of many copper alloys and more in particular in the bronzes. Second-phase hardening only played a minor role in ancient bronzes.

Contrary to pure metals, which have one single melting (or solidification) point, metal alloys have a solidification "interval". They start to solidify at a given temperature, which is lower than that of the pure metal and solidification is completed at still much lower temperature. This allows gases and air to escape more easily during solidification. Hence, casting of complex shapes becomes possible –a.o. by the lost wax process that was developed in Egypt– and work in the casting shop became easier to control.

The important impetus given by bronze to global trade and society organisation

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[22] After the Persian invasion, Themistocles and Aristeides appear to have made up their differences. But Themistocles soon began to lose the confidence of the people. The Spartans further accused him of treasonable intrigues with Persia. He was proclaimed a traitor at Athens and his property was confiscated.

Copper, Gold and Silver are three of the seven metals of Antiquity. The four other metals are Lead (from 3500 B.C.), Tin (from 2700 B.C.), Iron (from 1500 B.C.) and Mercury (from 750 B.C.). No new metallic elements could be extracted till the early second millennium A.C.
Of the four metals mentioned above, only iron succeeded in creating important hinges in technological and human history, as will be shown later on.
Lead and Mercury have their own particular history and –as an element– have certainly put their stamp on the history of technology.
Tin on the other hand, whose applications as an element were of less importance, has played a crucial role as an alloying element for copper in the Bronze Period.

The transition from the chalcolithic period into the bronze period is indeed one of the most important hinges in human history. What is less known however, is that that transition took place in two successive steps.
Rather soon after the establishment of copper smelting metallurgy, it appeared that some copper mines delivered a "copper" with a more yellow tarnish. It was a "copper" from which, compared to copper originating from other mines, sharper knifes and more wear-resistant axes could be hammered –up to a strength of 750 MPa– and from which stronger castings could be made. Analysis of objects and tools made from such material has shown that they were made from copper containing up to 2 wt % of arsenic, an alloying element that strengthens the copper by solid solution hardening.
It can be assumed that the first arsenic-bronzes were accidentally produced since arsenic and copper minerals commonly occur together in sulphide deposits. And as arsenic and arsenic-free copper ores both weather to form greenish oxide and carbonate minerals, it was difficult for our ancestors to distinguish. Modern metal analysis techniques have shown that the first bronzes produced in virtually all of Europe and the Middle East were copper-arsenic alloys, whose composition –including other "impurities" such as iron, antimony, nickel, bismuth, silver..- allowed to identify their mining sites. So, the axe of the famous 5000 year old Neolithic Iceman, whose corpse was found in 1991 in the Austrian-Italian Ötztal, consisted of copper with 0.22% of arsenic and 0.09% of silver. This allowed geologists to conclude that the axle was most probably cast from arsenic containing ores found in the Alps, and not from farther east.
After centuries of experience with the natural arsenic bronzes, metal smelters knew which copper ores allowed to produce the highest quality tools and weapons. In other words, ores with larger concentrations of arsenic were

identified. They then started to mix these with other copper ores and to produce in this way a variety of arsenic bronzes for different applications.

The arsenic bronzes determined the early Bronze Age from 3150 till 2500 B.C. They proved to be the best early copper alloys because of their hardness, their excellent wear resistance and their broad solidification interval. It is clear that for our ancestors, they were not more than "yellow copper"[23], as they did not know about the existence of the element arsenic.

This was no longer the case when the tin-bronzes came on the scene around 2500 B.C., because the smelting metallurgy of tin was already developed nearly 200 years before.

The tin-bronzes started to appear in Mesopotamia[24] during the third millennium B.C. They opened the so-called Middle Bronze Age.
The early smiths who produced the artefacts for the Royal tombs of Ur must have been astonished to find that combining a bit of tin[25], which has a hardness of 5 on the Vickers scale compared to 50 for copper, produced an alloy with a hardness of about 90, that could be raised by hammering to 228 and a strength of 750 MPa, hence twice as strong as hammered copper. Tin bronze thus was comparable to the best copper-arsenic alloys It was even easier to cast and had a corrosion resistance comparable to copper. On top of that, it showed the same workability and wear resistance and a similar attractive colour as its arsenic-containing counterpart.

Tin bronze metallurgy had two more practical advantages over arsenic bronze. First, by eliminating the highly toxic fumes produced when arsenic is roasted, it reduced the mortality of metal-smiths, who were vital members of society. Second, tin-bronze provided more predictable results as it commonly occurs as the oxide mineral cassiterite, which typically contains close to 80 % of tin. Without any knowledge of chemistry, the smiths experienced that is was much simpler to add a well defined quantity of tin metal or –sometimes– to estimate the quantity of cassiterite to add to the copper ore charge than to judge the arsenic content of a mixed oxide or sulphide ore.

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[23] Today, people still give the name "yellow copper" to the well-known brasses which are copper-zinc alloys.
[24] Earlier production might have taken place in the Indian Subcontinent.
[25] They had already made tin- bronzes by mixing cassiterite and copper ores in their furnace.

Tin bronze not only came into use for numerous small ornaments, but also for large statues. It opened the door for a real mass industry of agricultural and other tools, and, of course, of weapons.
However, replacing an arsenical ore with cassiterite was a mixed blessing. On the one hand, extracting tin from cassiterite in a charcoal fire is easy. On the other hand, cassiterite was scarce in the birthplaces of metallurgy and the few placer deposits found there were small, therefore quickly exhausted and soon forgotten[26]. Tin had to be purchased elsewhere.

For the people in the Eastern Mediterranean, the greatest known source of the white metal was situated in Kestel (eastern Turkey), in the Taurus Mountains. The Kestel Mine was in operation during the second half of the third millennium B.C. The ore was taken from Kestel to the nearby city of Goltepe where it was smelted. Since there was no copper at Goltepe, almost all tin was exported elsewhere to be alloyed with copper. Tons of tin were brought by Assyrian caravans to the southern Mesopotamian cities, but also west to the Hittites to get the bronze-work for their weapons and agricultural tools done. For the Assyrians, this deal was very lucrative. After the Assyrian period (1850 B.C.), the tin supply from Goltepe became depleted.

However, towards the end of the second millennium B.C., several new cassiterite sediments started to be mined and gradually, tin-bronze became as important for the civilisations all over Europe[27], as steel is for us today.

Greek and Roman historians[28] have documented later on, how placer cassiterite was transported to the eastern Mediterranean from Tuscany, Spain, Portugal as well as from the Erzgebirge (North-West Tsjechia). There is even a speculation that it was brought overland as tin metal from the Indian subcontinent. Taking the effort that went into mining, smelting and shipping tin into account, its price must have been extremely high.

The development of the Bronze Age in Western Europe deserves special attention. Among the earliest of the Western European metalworkers were

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[26] This might explain why from Egypt to the western Mediterranean, arsenic-bronzes only disappeared from 2000 B.C.
[27] and in fact also in India and China
[28] RICKARD, T.A., 1932. Man and Metals (2 volumes). Whittlesey House (McGraw-Hill), New York, p. 347-349

the Bell-Beaker people, so called for the distinctive bell-shaped clay cups buried with their dead. They were merchants and traders, possibly from Spain, who roamed Europe around 2500 B.C.[29]. They travelled widely, from Poland in the east to the United Kingdom and Ireland in the west, and from the Baltic Sea to the Alps. They were also excellent potters and smiths who knew how to smelt and cast copper, and made knives, spear points, hammers and axes for the people of the territories they crossed. But they did not know bronze yet. Sometime between 2300 B.C. and 1800 B.C., they became assimilated with inhabitants of central Europe, forming a new culture, known as the Uneticians. They are named after a small smelting site beside the village of Unetice (discovered in 1879), situated on the northern outskirts of Prague, about 80 kilometres from the already mentioned, ore-rich Erzgebirge. There, based on the Bell-Beaker metallurgical know-how and thanks to the presence of rich metal deposits in the region, including tin, they gained experience in the production and use of tin bronze. The Uneticians spread throughout the valleys of Germany and the adjoining lands to the west and north. Their bronze ware has been found in graves as far away as England and Sweden[30]. By 1500 B.C., the Uneticians had become rich and were the dominant people of Central and Western Europe[31].

Another panel of West-European bronze history is to be found in the western parts of the British Isles. Archaeological evidence indicates that by about 2000 B.C., metal mining had been, rather independently, developed in Ireland as well as in Cornwall and Devon (England). Most of that early mining activity was directed towards gold and copper. Determining when bronze was produced there is more difficult. As was mentioned, the first tin bronze that appeared in these regions was probably imported by the Uneticians. However, during the Middle Bronze Age, during the so called "Celtic Millennium", the Cornwall-Devon cassiterite mines started to be

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[29] E.G.Garrison in Physics today-online – www.aip.org/pt/vol-54/155-10/p32.html

[30] NIEDERSCHLAG, E., PERNICKA, E., SEIFERT, TH., and BARTELHEIM, M., 2003. The Determination of Lead Isotope Ratios by Multiple Collector ICP-MS: A Case Study of Early Bronze Age Artefacts and Their Possible Relation with Ore Deposits of the Erzgebirge. Archaeometry, University of Oxford, Oxford, p. 61-100.

[31] KNAUTH, P., 1974. The Metalsmiths: The Emergence of Man. Time-Life Books, New York, 160 p.

exploited. Trading relationships were developed for tin and the region played an increasing role as a vital source of tin for the more advanced cultures in the eastern Mediterranean[32-33]. Transport routes developed over land and Phoenicians sea-traders left the Mediterranean for the Atlantic, sailing and rowing for tin in Cornwall.

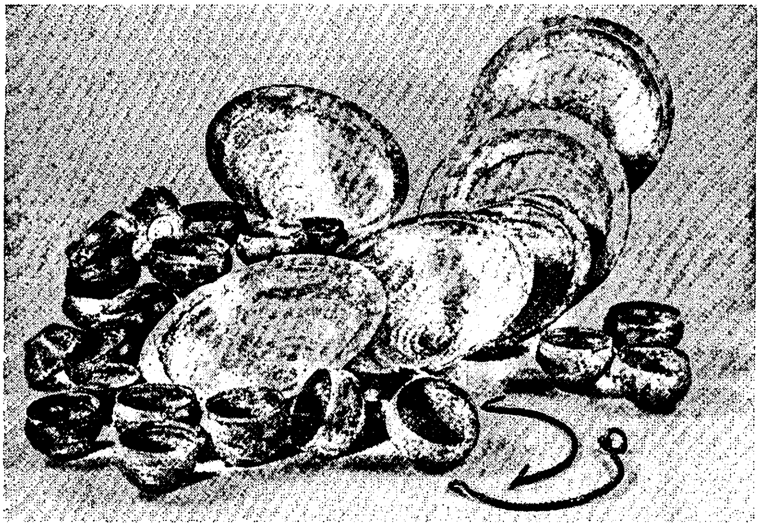

Fig. 5 :Bronze cups, dishes and handles. 8th cy BC. Römisches Museum Augsburg Inv. VF 97 – from the „Ehingen-Burgfeld Bronzefund“ [26]

So, from East to West, bronze metallurgy brought important innovations to society. In order to produce bronze, resources of copper and tin were needed. These were dispersed, leading to complex connection and transport networks. Mining regions such as Rio Tinto in Spain, settlements in the Harz, the Erzgebirge and Steiermark, Cornwall and Devon became rich; but also regions that controlled the passage of metal transports, like Tongeren in Belgium and Biberacte in France benefited from the new business. The production of objects soon exceeded the needs of the own region; a distribution economy was created and competition became a rule. This

[32] Jacques BRIARD " l'Age du Bronze en Europe- Economie et Société 2000-800 avant J.C." –Editions Errance, Paris, 1997
[33] Herbert DANNHEIMER and Rupert GEBHARD "Das Keltische Jahrtausand" Verlag Philipp von Zabern – Mainz - 1993

diversified the demand and created conflicts between neighbours. "Chefferies" arose, characterised by a powerful elite, which controlled, defended and extended territories and which underlined their prestige with ornaments of gold, silver and amber and with numerous bronze arms and implements.

On the scale of the Mediterranean and Europe, because of Bronze, "globalisation" became a reality.

A WORLD WITHOUT STEEL WOULD BE ANOTHER WORLD

Phase and Other Transformations in steel

Iron is one of the metals most abundant in the earth's crust, mainly in the form of various iron oxides.
The metal iron has a melting point of 1537°C. It has the particular property that it changes its crystal structure when being cooled from red heat to a lower temperature. The high temperature phase is called austenite, the low temperature phase is ferrite. In the case of pure iron, the transformation from austenite to ferrite occurs at 910°C.
But 100% pure iron is not easy to make. Then another important property of that metal is the eagerness with which the high temperature phase (austenite) takes carbon in solution. Up to a content of 0.8 wt%, the tiny carbon atoms in the lattice increase the stability of the austenite, causing the transformation temperature to decrease down to 721 °C.

Also the molten iron is happy with more carbon in solution so that the solidification temperature of the material decreases concomitantly.

The low temperature phase (ferrite) of the solid iron has an extremely limited solubility for carbon. Therefore, as soon as the carbon concentration in the austenite exceeds one tenth of a percent, on cooling down and passing the transformation temperature of 721°C, between the already formed ferrite network, an equilibrium second phase mixture becomes visible, usually in the form of tiny lamellae of cementite with composition Fe_3C, separated by ferrite lamellae; that mixture is called pearlite. With increasing carbon content, increasing amounts of pearlite appear until at nearly 0.8% carbon, the whole low-temperature structure has become pearlitic. More carbon hence leads to more pearlite resulting in stronger steel. Up to that composition, the material is called steel and it keeps a good workability.

Beyond 0.8% carbon, separate cementite boundaries start to appear around the pearlite regions. They embrittle the material and so we gradually leave the "steel" region of compositions, approaching the "cast iron" region. There, we observe a further decrease in melting(solidification) point of the material down to 1150°C at a carbon concentration of 4.3% delivering, on transformation, a hard but brittle mixture of cementite and pearlite.

Steels with a carbon content below 1 wt%, have another interesting property. When rapidly cooling them from the austenite region, equilibrium structures cannot be produced, because the mobility of carbon is too low to form the equilibrium phases ferrite and pearlite. Instead, a metastable, distorted ferrite-like structure is formed which bears the name martensite. Martensite is extremely hard and brittle in the as-quenched condition, but becomes tough –without loosing its hardness–, by heating it for a short period at about 250-350°C.

From bronze to iron: victory by necessity

If the origin of copper metallurgy was the result of the curiosity of pottery craftsman, the transition from the Bronze to the Iron Age shows that not curiosity but rather necessity was the mother of invention.

Indeed, for about two millennia, up to about 1200 B.C., the civilisations of the Eastern Mediterranean had satisfied their needs for metal tools and weapons with copper and bronzes. Nevertheless, there is now ample archaeological evidence that around 1200 B.C., iron was already known for a long time as a workable metal. There were obviously good reasons to prefer bronze to iron. The high melting point of iron could not be attained by the early metalworkers and, as will be shown below, compared to copper, a much more complex extraction method had to be used. For the same reason, the thus obtained iron could not be molten and cast. Iron articles hence were individually shaped by forging, which was a more arduous process than casting. An 11% tin bronze could be brought to a tensile strength of almost 800 MPa by hammering whereas the iron available in those times could barely be strain hardened to 700 MPa. And last but not least, bronze had a better corrosion resistance and was so much prettier to look at than rusted iron.

In the second millennium B.C., the Hittites were known to be the best metalworkers of the whole area. They are also recognised to be the first to succeed in extracting iron from iron ore –hematite and magnetite–, by finely intermixing the ore with charcoal, heating it with sufficient blow from

blowpipes and primitive bellows, to 1200°C for a long time thereby reducing the iron oxides to a hot porous iron mass, filled with a viscous iron silicate – or fayalite– slag. The metalworkers thus drew from the furnace a mass of spongy iron, reheated it in a forge and literally squeezed out the slag by hammering. The thus obtained bloom consisted of a rather low-carbon iron that in many cases still contained entrapped stringers of slag. Careful control of the furnace operation was needed in order to prevent too long contact times between the iron and the charcoal, which could lead to an excess carbon in the metal, making it as brittle as glass. The efficiency of the first primitive furnaces was very low, as archaeological estimations tell that 500 kg of charcoal was needed to produce 100 kg of metal, and only 50% of the iron content of the ore was reduced to metal.
There was thus no technical reason to start an Iron Age, if not late in the second millennium B.C., invaders from the so-called "Peoples of the Sea" led to the collapse of a number of empires including that of the Hittites. As a consequence, bronze became scarce as the supply of tin and even of copper to the bronze smelters of the Eastern Mediterranean was suddenly interrupted.

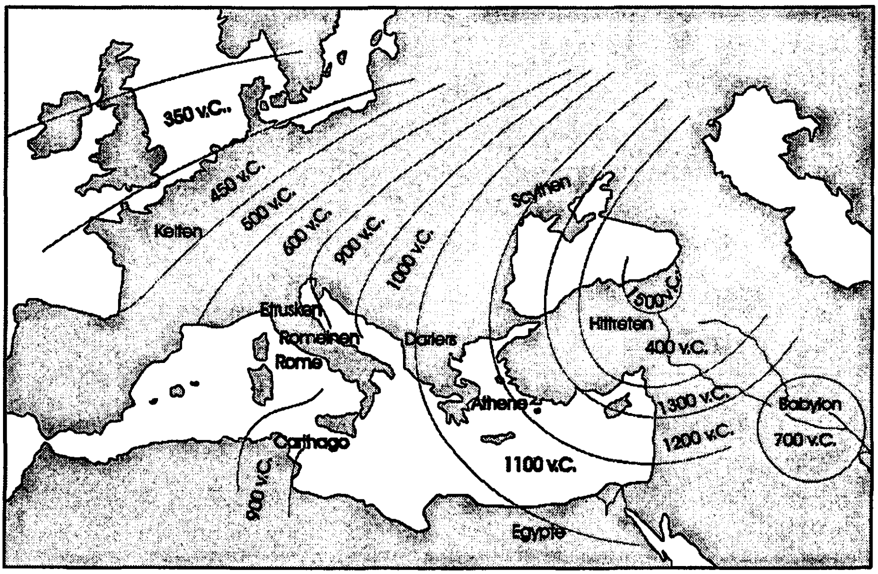

Fig.6 : Chronology of the spread of iron metallurgy from its origin in Anatolia 1500 B.C.

From then on we see a rapid rise of iron as a substitute for copper and bronze objects, even when after 900 B.C., tin became available again and bronze remained in use e.g. for the breastplates and helmets of the Greek soldiers during the Persian wars. The ironmasters of the time had by then learned to control hardness and strength of the iron they made, by carefully looking at colour changes of the flames and the time of heating –They did not yet know about the carbon content, nor about the amount of pearlite in the material–.

Steel created and destroyed empires

The sponge iron process described above has remained the unique iron-making technology from then on till the late Middle Ages. As iron ore was abundant everywhere, the technology spread east- and westwards–see fig.6-. It had a great impact on agriculture and civil engineering –fig.7-, and still more on the military history of the last millennium B.C. In the long Persian wars, Greek soldiers indeed had bronze breastplates but iron daggers and spears. And for the conquest of Palestine by the Babylonians, for the Phoenician-Carthagenian colonisation of Spain, for the journeys of the same Phoenicians to England, for the Phalanxes of Philip II and Alexander the Great, for the Roman legions in the Punic wars, huge amounts of wrought iron were required. Estimations tell that 20 to 30 tons of iron metal was needed for a well-armed Roman legion. From those times, remnants of numerous low-furnace bloomeries were found all over Europe, to such an extent that around 1900 A.C. the blast furnaces of Katovice in Poland were still partly charged by nearly 2000 year old slag heaps from the nearby region.

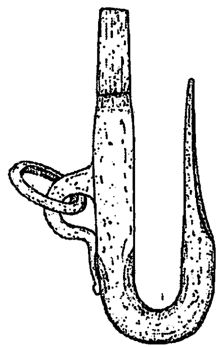

Fig.7: Forged iron hook from Roman times[34]

However, the use of iron for high-quality arms and tools would not have been possible without the development of steel hardening. From the beginning of the 10th century B.C., blacksmiths were intentionally hardening high-carbon steel by quenching it from the austenite region, transforming it into martensite and slightly reheating it (the so-called "tempering" process) for restoring its toughness.
Somewhat later, the process of surface carburising low-carbon steel after which it was quenched and tempered, was invented. As a result, tools and weaponry that combined high tenacity and hardness could be made.

A passage in the Odysseus describing him and his men being trapped in the cave of Polyphemus, the one-eyed giant, describes how they decide to try to get the giant drunk and blind him by snatching a burning olive trunk out of a fire and thrusting it into his eye "As when a man who works as a blacksmith plunges into cold water a great axe which hisses aloud... since this is the way steel is made strong, even so, Cyclop's eye sizzled about the beam of the olive."[35].
Again, our ancestors did not know what was really happening in the material. It has even been told that carburising steel implements before hardening them, was considered to be a purifying rather than an alloying process.

Preparing the industrial revolution: the birth of capitalism
After the fall of the last Roman Emperor, Roman Augustulus, in 476 A.C., mood and capital were lacking to revive the exhausted economy. Because of the scarcity of gold and silver for currency, large portions of Europe were forced into a barter economy and slipped into obscurity. For the next thousand years, tools and weapons were made with the same materials and the same technology as in Roman times.

The Roman iron furnaces were already improved versions of the primitive furnaces used in the old Mediterranean empires. They were able to increase the production per run from 5 to 25 kg. But even if their furnaces were

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[34] Marc Lodewijckx et al. in "A 3th century collection of a Roman villa" in Acta Archaeologica Lovaniensia 33, (1994)
[35] "How the Iron Age began" R. Maddin, J.D. Muhly, T.S. Wheeler – Scientific American pp 122-131

somewhat larger in height than in the past, they were still working as "bloomeries", making sponge iron, and blown by bellows activated by human power.
Towards the end of the first Millennium, while the rest of Europe still stagnated, ironworkers in Catalunia, Spain, managed to improve furnace technology –probably stimulated first by the Visigoths and later by the Moor occupants–. They developed a hand-blown new design of smelter –known as the Catalan furnace–, enabling them to produce 175 kg of iron per run. Further increases in capacity were realised by smelters in Austria, who developed the "Stückofen" which was three or more meters high, nearly twice as tall as the Catalan furnace.

But the most striking novelty at that time was the use of watermills to drive the bellows, thereby being able to generate blasts that reached the top of the furnaces.
The large quantities of ore and charcoal needed from this moment on, demanded for mechanical devices to drain mines, to crush ore and to forge hot iron. Waterpower that had been used since several centuries for grinding corn and for winnowing felt, now became the basic instrument for large-scale mechanisation all over Europe. Waterpower was therefore one of the keys of Europe's emergence from the Dark Ages.

Monasteries were extensively involved in the construction of watermills for all kinds of purposes. Later, they were followed by princes and kings who owned several mining sites. In order to install the infrastructure needed for their operations, both mine-owners and ironmasters required substantial amounts of capital. New institutions and new methods arose to finance these large-scale projects, and with these came the birth of capitalism. Rich German and Italian families took the lead in developing the European banking system.

Preparing the industrial revolution: the two-stage steel making process
The furnaces became taller and the air blasts more powerful. Therefore, the ore was exposed to charcoal at higher temperatures and for longer times. Here and there, iron masters started to notice liquid iron to flow to the bottom of their furnace. Although at first, the liquid iron presented a problem to the smelter, it did not take long before creative ironmasters started to tap this iron and noticed that it could be cast in moulds: they had produced cast iron with a carbon content of 3 to over 4 wt%, with a melting point as low as

1150 °C. In the German-speaking part of Europe metallurgists spoke about the "Flussofen" as opposed to the "Stückofen".
The material was very brittle, but, living in a time with increased technical and market opportunities, compared to centuries before, they started to appreciate the value of the previously undesired cast iron for use first in church bells and hearth plates, and later in cannons[36] and cannonballs – gunpowder having been introduced in Europe around 1300 B.C.–. The new market that had emerged led them to make a new furnace design, where ore and charcoal were charged at the top, after which they slowly sank downwards, reacting with each other to produce liquid cast iron –or better "pig" iron because of numerous impurities still present– reaching the bottom leaving a lighter liquid slag layer above the metal melt. Liquid iron and slag could subsequently be tapped.
The predecessor of the modern blast furnace was born around 1400 A.C., according to metal archaeologists "somewhere in the Rhine provinces with the French, Belgians and Germans probably sharing honours in this great technological triumph"[37]. However, the first blast furnaces were not very reliable because of irregularities in their functioning: there was no certainty whatsoever that every production run would be successful and yield molten iron. They moreover consumed a disproportionate amount of fuel. This might explain why Steiermark in Austria, which produced very high quality iron, did not use a blast furnace until the 18th century.

The reasons are obvious: the majority of applications still required wrought steel, made by the traditional blooming process.

And it is here that the metalworkers of the Liège region came into play. They were known to be excellent craftsmen, able to make knives and nails from "fer, plus fort que le fer!"[38]. Already in the early second millennium, they built furnaces of 100 kg of iron per run, later followed by "Stückofen" type furnaces which produced about 700 kg per run. Moreover, they were amongst the first to use watermills for powering bellows and hammers. They managed to let their "forges" work continuously, even in dry seasons, by building water reservoirs in the vicinity of the furnaces. On top op that, they had a good knowledge of the variety of steel qualities, using Lorraine ores

[36] Far into the 17th century gun barrels were made of bronze.
[37] D.A. Fisher in ""The Epic of Steel" – Ed Harpe and Row NY – (1963) – see also : http://www davistownmuseum.org
[38] Iron, stronger than iron

for common items –of lower quality because of higher phosphor content–, but preferred the more expensive –low phosphorous- iron from Northern Spain for the highest quality knives and nails.
They also had several high furnaces, built in the Liège region, producing cast iron for applications such as stoves, hearth plates, architectural ornaments...

It was in that same region of Wallony that towards the end of the sixteenth century the development took place of what was soon called "the Walloon Furnace". It was a technology that transformed the carbon-rich and often impure cast iron from the blast furnace into a high-quality, low carbon wrought steel. Cast pigs from the blast furnace where progressively re-molten in a hot oxidising flame that removed carbon and impurities from the falling droplets. The purified iron droplets fell through the fayalite (FeO.SiO2) slag layer and solidified on the bottom of the so-called "affinerie" or "finery" furnace. The thus produced iron bar was then reheated in the "chaufferie" or "chefery" in order to prepare it for forging.

The production of wrought steel in two successive stages was a precursor of modern steel making, which is still used in more than 90 % of the steel industry today. It is therefore justified to call the development of the Walloon furnace a "proto-industrial revolution".

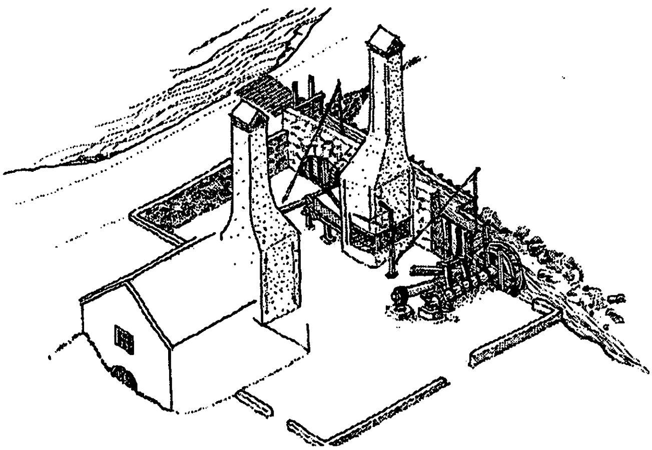

Fig.8: *Drawing of a Walloon type furnace and forge from Österbybruk, Sweden. At the left the finery (the bellows at the backside are not visible), at the right, next to the river, the chaufferie and the hammer*[33]

This new technology was introduced all over Europe, and accelerated the development of the steel industry in Great Britain and even more in Sweden. Indeed, up to the sixteenth century, mining and metallurgical industries were generally more advanced on the continent than in Britain. With the extension of the Commonwealth, however, the demand for iron increased dramatically, driven in part by the appetite of the shipbuilders for anchors and rivets and of military for firearms and cannons.[39].

England then, eager to become self reliant in the production of steel, recruited a substantial number of Walloon ironworkers, who brought the Walloon process with them, thus speeding up the development of the British steel industry.

The contribution of Walloon ironmasters to the Swedish steel industry is considered to be even more important, to the extent that some Walloon historians see in their fellow countryman, Mathieu de Geer, who organised the emigration of the Walloon metalworkers to Sweden, "the Father of the Swedish industry"[40].

Several conflicts in Europe during the 16th and 17th century severely hit the Walloon iron industry, creating a socio-economical crisis in the region. Between 1620 and 1640, about five thousand people accepted the invitation of Louis de Geer, uncle of Mathieu, to join the Walloon families that had already left the Low Countries for religious reasons. Louis de Geer had lived in Sweden from around the turn of the century and had become the owner of several ironworks –moreover, wealthy as he was, he became the banker of King Gustav-Adolph II–. He understood that in order to further develop the iron industry in Sweden he needed to import qualified personnel from abroad and it is that what his nephew Mathieu arranged for him. Most of the Walloon families settled in the region of the Dannemora mine, close to Uppsala, which was known to have the most abundant, but also the best, iron ore in Europe. They implemented the Walloon technology –fig. 8-, mastered to the extent that it allowed producing numerous variants of steel. Some of

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[39] Despite laws passed by Elisabeth I, limiting the export of cannons. The British trade was so lucrative that smugglers managed to export large numbers to Spain. When the Spanish Armada weighed anchor to invade Britain in 1588, the majority of its guns were returning to the place were they had been manufactured.

[40] "Sur la trace des Wallons de Suède" Ph. BASTIN – in « Terre de Durbuy » 2003

these variants were regarded as professional secrets, not to be divulged, not even to the learned experts of Jernkontoret (The Swedish Association of Ironsmiths). Two centuries later, Christopher Polhem, one of the great Swedish technicians of that age, was almost a fanatic in supporting the Walloon iron when he wrote "all other bar iron anywhere in the whole kingdom ... is as good as useless and to be rejected on account of the infidelity and deceptions of its art"[41].

It has been assumed that Sweden was exporting about 4000 ton of iron before the first Walloon furnaces were installed. Already in 1650, 18000 ton was reached. Then, by the 1740's, the average export had risen to 42000 ton. Nearly half of that amount, mostly in the form of bars, was absorbed by Britain. In the midst of the 18th century, Sweden had indeed become Europe's largest exporter, thus representing a substantial share of the international trade.

It goes without saying that the expertise brought into Sweden by the Walloon immigrants has given a historical impetus to the Swedish steel industry. The immigrants have integrated very well in Swedish society and the nearly fifty thousand descendents of today are proud of their origin. About two thousand of them belong to the "Vallonättlingen", –descendents of the Walloons of Sweden– a society that has the objective to keep the memory of the contribution of their ancestors to the Swedish economy alive.

Making the industrial revolution possible: from charcoal to coke

Already during the 1760's, Russian imports of steel in Britain reached the Swedish level. Several researchers stress that the reason for the stagnation of the British home industry was the menacing deforestation of Britain, because of the immense quantities of charcoal fuel consumed. Between 1588 and 1630, the cost of charcoal indeed increased from being one half to nearly three quarters the cost of smelting iron. The state of the British forests thus had become an obstacle to the British iron expansion and the country was obliged to turn to younger and hitherto less affected economies[42].

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[41] "Swedish Iron in the 17th and 18th Centuries-Export Industry before the Industrial revolution." Karl-Gustaf Hildebrand – Jernkontoret Berghistoriska Skriftserie 29 - 1992

[42] Some British scholars in economic history stress that it was not the shortage of charcoal, but standing concerns about labour cost –because of the large amount of work-hours that went into charcoal burning– that made steel, from the economically less-developed Sweden, cheaper than the British steel.

In every case, by the start of the eighteen century, the price of imported steel increased and the situation worsened.

First trials to use coal instead of charcoal for the production of pig iron, had already been performed in the early 17th century. These tests were, however, not successful because the sulphur content, coming from the coal, in the so-produced iron was too large, hence causing brittleness[43].
Decades later, a certain Abraham Darby, son of a Quaker family of farmers in Worcester-shire had not only learned the art of forging in his fathers' workshop, but also the art of making coke. Neighbouring brew-masters indeed used coke for drying malt, since the use of coal during this drying process, caused the beer to absorb evaporating gases, which resulted in an unpleasant taste. The entrepreneurial Darby, who was aware of the increasing problems of the iron industry in his country, came to the conclusion that coke should enable a new future for the iron industry. He leased ironworks at Coalbrookdale near the Severn River. The first coal roasting trials did not result in the best quality coke, but fortunately the coal mined in that region was of low sulphur content. In 1709 he made the first successful production run, not yet aware that he had made a most important contribution to the first industrial revolution that would follow.
Then, in spite of Darby's success, the use of coke was for a long time only marginally accepted as a substitute for charcoal.
But the Darby family remained self-confident and markedly innovative. Darby's son, Abraham II, cooperated closely with the developers of the atmospheric engine (Thomas Newcomen) and the steam engine (James Watt) for whom he produced cast iron boilers. These were used to pump water from the coalmines. Inspired by this application, Abraham II decided to use a steam engine to pump water to a reservoir at a higher level, allowing his furnace to operate continuously. In 1755/56, he built two new furnaces with direct powering of the bellows by steam engines. He thereby succeeded in making pig iron of an extremely good quality, that could be refined in an adapted version of the Walloon furnace into wrought steel.
In 1779, Abraham III, continuing Darby's steel tradition, then built the famous Ironbridge over the Severn with 25-meter long rib castings, demonstrating that iron could be used for large structures. And the subsequent descendents of Darby continued to operate the Coalbrookdale foundry until well into the twentieth century.

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[43] Sulphur atoms migrate to the grain boundaries and this leads to inter-granular fracture on subsequent hammering or forging.

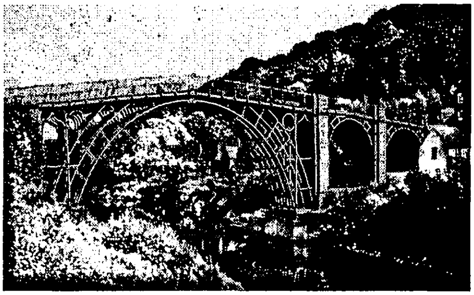

Fig.9: The Ironbridge in Coalbrookdale (1779) over the Severn river.

Towards the end of the 18th century, several ironworks in Wales, England and Scotland had already adopted Darby's technology. Most of them were small to medium-size initiatives that did not require great amounts of capital, but gave in all cases a great autonomy to the region. In 1800 the English ironworks already produced 100.000 ton, five times as much iron as the European continent; in 1850 –two years before the first coke-fuelled blast furnace was put in operation in Müllheim, Germany– the production amounted to 900.000 ton, still ten times that of Germany. And at the dawn of the First World War, England produced nearly 10 million tons of steel ... but in that same year Kaiser Wilhelm's Germany had already made up arrears!

Further developments in the iron- and steel industry were without doubt of equal importance. These include the transition of the Walloon finery to transform pig iron into steel into the puddling technologies and further into the Bessemer and Thomas blowing processes and the introduction of the use of preheated air in the blast furnace. And last but not least Europe saw the development of the Henry Cort roll forging process, a predecessor of the rolling mills, which have evolved into indispensable production equipment of automobile steel sheet.

But the metallurgical hinge of greatest historical importance, is without doubt the substitution of charcoal by coke for making iron, and the demonstration that the iron obtained in this manner could be used for machines, train rails, large engineering constructions, and a completely new steel architecture, thereby completely changing the landscape and the society of 19th century Europe. Unfortunately, new societal problems were equally created: an oppressed workers class was developing, and new inequalities appeared all over Europe. They led to revolt and rebellion all over the continent. It was the most negative aftermath of the first industrial revolution, too often forgotten to mention when describing the technological – and in the long term of course general prosperity creating- jump that was made.

ALUMINIUM MADE MODERN AIR TRANSPORT POSSIBLE

Precipitation hardening

In several alloys, the solubility of alloying elements in the base metal matrix is limited and beyond a given concentration, a second phase is formed. However, the solubility often increases with increasing temperature. When such an alloy is quenched from a high temperature, a supersaturated solid solution is obtained because of the small mobility of atoms at low temperature. When holding the quenched material for some time at room temperature or –often more practical– at a slightly increased temperature, the material evolves into its equilibrium two-phase state by precipitating small particles of that second phase. The smaller those particles are, the more they hinder dislocation movement, and hence, the stronger the material. This mechanism is called precipitation hardening. The position achieved by precipitation hardening alloys in our modern economy is significant. The leading example of it is doubtless that of the precipitation hardened aluminium alloys.

In 1782, Antoine Lavoisier had prophesied that "metals" should be present in the so-called "earths" –lime, magnesia…– but the means to detect them were not available in his time. It was left to Sir Humphrey Davy to separate several alkali metals from their oxides. He had learned about Volta's "voltaic pile", and set out to use such a pile to decompose various chemical compounds back to their component elements. With this technique, Davy could extract sodium, potassium, magnesium from their molten hydroxides and chlorides, but he was unable to extract the metal hidden in alumina (Al_20_3).

It was a Danish scientist, H.C. Oersted who could extract the first drops of aluminium from aluminium salts in 1825. But Oersted did not attach great importance to this new metal, nor did Friedrich Woehler who succeeded in producing somewhat larger drops. Finally, it was Henry Sainte-Claire Deville who developed an extraction process independently, that delivered sufficient quantities of aluminium to impress the visitors at the 1855 Paris

exhibition and not in the least the Emperor Napoleon III. The latter asked to meet him to share his views on the use of the new light metal for knots and breastplates for the Army and for spoons and forks for State Banquets.
However, since the new metal was as expensive as silver, only some small-scale applications –jewellery and artistic works like the Diane de Gables in the Louvre, and the cap of the Washington monument (1884)– existed at that time. Large-scale applications had to await the electrolytic process that began to supersede Deville's in the 1890's.
Oersted's and Deville's extraction processes indeed demanded electric batteries and large amounts of other metals, namely sodium or potassium. But as soon as an inexpensive source of electricity became available, thanks to the development of the electric generator, Charles Hall[44] and Paul Héroult developed an electrolysis cell in which alumina was dissolved in molten cryolite and electricity was provided from a nearby power plant. Circumventing the need for costly batteries to reduce the aluminium-oxide, the price of aluminium was reduced from 15 $/kg to only 1 $/kg. However, the fabrication of aluminium still remained too costly until the Austrian Karl Bayer developed a process to transform the bauxite ore –which contains aluminium-silicates– into alumina.

Thus, humanity had to wait nearly two millennia after Metal Antiquity before one of the most abundant metals in the earth's crust could be extracted from its ore.
Our ancestors indeed did not know that the reactivity of elements or the stability of their oxides increases from silver to copper, from copper to iron and very dramatically from iron to aluminium. The more stable the oxide, the more difficult it becomes to extract the metal.

The potential for the mass production of aluminium was present, the market, on the other hand, did not develop at the same pace. Despite the advantages of this metal, being three times lighter than steel, having a brilliant lustre, being corrosion resistant and at first sight easy to cast because of its low melting point, many problems were encountered upon trying to industrialise the production process. The infrastructure and know-how of the already established steel industry, e.g. its rolling mills and forging presses, proved unsuitable. The castings often had an inferior quality because of numerous

[44] Charles Hall was a student of F.F. Jewitt, the latter having been taught by Humphrey Davy. So we can understand why Jewitt inspired Hall to look for a cheap production method for aluminium.

shrink- and blowholes and although cold working could strengthen the material, the maximum tensile strength that could be obtained by strain hardening was far below that of the iron and copper alloys in use.

A great deal of the above-mentioned problems was solved with time. And as the price of the metal started to drop further following the turn of the century, new applications arose. The new metal was used increasingly for electrical transmission and auto engineers found it to be excellent for cast engine parts. But aluminium would never have attained its position as second important metal towards the end of the twentieth century, if the precipitation hardening potential of aluminium alloys had not been revealed.

Alloys that possess extensive precipitation hardening capabilities, have been used for centuries. There is, however, little, if any, evidence that this capability was recognised or used. Only recently have the abnormally high hardness and brittleness of some ancient silver coins, containing a few percent of copper and about one percent of lead, been attributed to extended natural aging – of course unintentionally obtained –.
Towards the end of the nineteenth century, some understanding of the crystalline nature of metals had already been acquired and different thermal treatments had been developed for steel and its alloys. The thermal practices for non-ferrous alloys, on the other hand, were generally limited to preheating for hot working and annealing of cold worked material. Phase diagrams were only roughly known and solubility limits had rarely been subjected to detailed investigation. The first author to mention decreasing solubility with decreasing temperature was H.W.B. Roozeboom[45] stating that "a solid solution may reject one of its components or a compound, as does a liquid solution, when it is cooled, this was an entirely unknown phenomenon a few years ago, but it has now been demonstrated in some cases which have been the object of studies by my pupils".

In 1909, the "Deutsche Waffen und Munitionsfabriken AG" persuaded Alfred Wilm, at that time only recently appointed head of the metallurgical department of the "Zentralstelle für Wissenschaftlich-Technische Untersuchungen" near Berlin, to initiate a research program to develop a light alloy which would be suitable for the production of cartridges for infantry weapons and with a workability, machinability and stability similar to that of a 72% Cu cartridge brass.

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[45] Roozeboom H.W.B. : Ztr. Für Physikalische Chemie 34, p.437 - 1900

Numerous treatments were tried out on aluminium alloys with copper, magnesium, manganese and several patents were taken. Some results were very spectacular, e.g. tensile strengths of over 400 MPa, which is more than double the strength of unalloyed aluminium. Unfortunately, the results were inconsistent and large variations occurred.

One story then explains how Wilm and his assistant, Fritz Jablonski detected the crucial importance of ***holding time***. It was a Saturday night and Jablonski wanted to rush home. But at the urgent request of Wilm, he had hurried to do a hardness test on a piece of Cu-Mg-Si alloy that had just been taken out of a furnace and quenched from a temperature of 520°C. The result was not very promising, as the hardness was only slightly higher than prior to the treatment. Since he was not convinced by this result, Jablonski repeated the test on Monday morning and found a spectacular increase in hardness. Those results were so intriguing that Wilm and Jablonski decided to repeat the heat treatment and measure the sample's hardness after several hours of "aging" at room temperature. Their results were shown in the graph of the figure 10, which was the first published PH graph and was followed by hundreds of such graphs in the decades that followed.

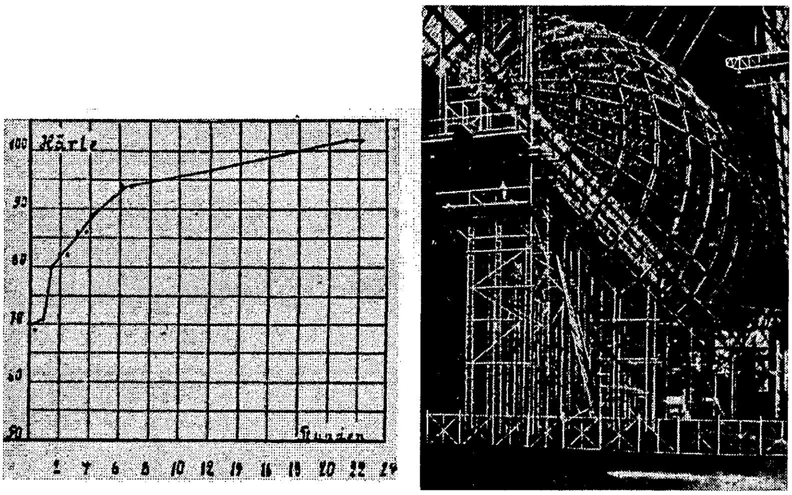

Fig.10 : The first aging curve made by Wilm in 1911 and the skeleton af a Zeppelin, representing the structural application of aluminium[46]

[46] H.Y.Hunsicker and H.C. Stumpf "History of Precipitation Hardening" in "TheSorby centennial Symposium on the History of Metallurgy" American

The Berlin Centre did not see an improvement in formability compared to the brass cartridge material and was therefore not really interested in commercialising the patent; therefore Wilm took it with him to the Dürener Metallwerke. The precipitation-hardened material therefore obtained the name Duralumin. The first successful production run amounted to 12.75 ton of which ten ton was used for the construction of airships.
The Zeppelin Airship Factory in Friedrichshafen indeed initiated structural experiments towards utilising the greater strength of this material in order to optimise the design of the skeletal framework (fig.10). During the First World War, production volume increased to 720 ton in 1916, of which dozens of airships were made.
In this same war also began the first series production of an all-metal airplane, the Junkers F13, with its complete body made of aluminium sheet, thus replacing the wooden airplanes of the past.
When later the stronger Duralumin alloy was considered, which unfortunately had a lower corrosion resistance than pure aluminium, a product called "Alclad" was developed. This product consisted of a strong alloy precipitation-hardened core, physically sandwiched between thin layers of nearly pure aluminium.
Further improvement of the precipitation hardenable aluminium alloys took place in subsequent decades, and aluminium has remained ever since *the* construction material for the body of commercial aircrafts.

ELECTRICAL CONDUCTIVITY, STRUCTURAL PERFECTION AND MATERIAL PURITY: HINGES OF THE COMMUNICATION ERA

Metals have large number of free electrons, which are not bound to individual atoms. These negatively charged particles easily move when under the influence of an applied voltage. However, along their path they collide with lattice atoms or with irregularities in the metal structure such as solute atoms, dislocations, vacancies and second phases. These "lattice defects" reduce the mean free path between two collisions, thus increase the electric resistance of the material. Hence, cold deforming, impurities or alloying elements reduce the electric conductivity of metal conductors like silver, copper, aluminium, etc..

Society of Metals – ed. C.S. Smith – Gordon and Breach Science Publisgers NY (1963)

Compare a metal like aluminium with silicon. The two elements are neighbours in the Periodic Table, which means that they are nearly equally light. Their metallic appearance is also similar. The electrical conductivity of aluminium is, however, eleven orders of magnitude (10^{11} times) better than that of silicon. The reason for this can be found in the completely different and much stronger bonding in silicon[47]*, where electrons are forced to be shared between neighbouring atoms. When a voltage is applied, the electrons remain immobile, until the voltage reaches 1.1 Volt. Once the –covalent– bond is broken, the electrons can move freely. The silicon crystal hence acts as a switch: no current flows below 1.1 Volt, whereas above 1.1 Volt, the metal conducts the current. Silicon therefore is often described as a semi-metal or a semiconductor.*

Of course, any disturbance of the perfection of the silicon crystal also has its effect on the performance and reliability of this semiconductor. Foreign atoms bring new conducting particles into the lattice. When this is done intentionally and under strictly controlled conditions, we are dealing with "doped" semiconductors– which have a higher –but controllable-conductivity than pure silicon. This doping is needed in order to make transistor elements. But other disturbances, like grain boundaries, dislocations, vacancy clusters have uncontrollable effects and always deteriorate the quality of the material.

The first transatlantic cable

We admire the versatility of authors and scientists of Renascence and Enlightenment times. They were able to exceed the boundaries of their own discipline.

One example of this versatility is found in William Gilbert, born in Colchester under Elisabeth I. He graduated as a medical doctor in 1569 at Cambridge. He became a member, and in 1600 even the president, of the Royal College of Physicians in London. However, this did not prevent him from editing, in the same year, his book "De Magnete", which is in fact the first standard work about electrical and magnetic phenomena. Although the book was not free of alchemy-like statements and parts of popular belief were treated seriously –like the influence of garlic on the performance of the compass–, Gilbert was the first to clearly distinguish between magnetism and static electricity. Magnetism, he wrote, is the soul of the earth, indicating the

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[47] Silicon has a diamond-like lattice with covalent bonding between the atoms. The much stronger bonding also explains the great difference in melting point between aluminium (660°C) and silicon (1414°C).

relationship between the polarity of the compass needle and the earth's magnetism. Static electricity, on the other hand, is the effect that occurs when a material, after having been rubbed with a cloth, attracts dust particles and chaff, or the effect that leads to the undesired experience that you get an electrical shock when touching a metallic doorknob after having walked some steps on a carpet. Gilbert called this phenomenon "electric force", a word based on the old Greek word for amber, the material he used for his experiments on static electricity. Thus, four hundred years ago, the etymological foundation was laid for concepts like electric charge, electricity, electro-technics, electronics etc... words which nowadays belong to our daily vocabulary.

In 1729, the English chemist, Stephan Gray, observed that electricity being generated in a piece of amber or glass could be transported over several hundreds of meters through a brass wire. Electricity, he concluded, is not inherent to a given place in the material, but can move through this material. The subsequent development of electricity consisted of a series of inventions, driven by a combination of curiosity, entrepreneurship and accidental luck. We limit the further text of this part to some topics, which illustrate the growing attention that was given to the metal copper.

Benjamin Franklin (1706-1790) closely followed the developments that were taking place in electricity. He was especially interested in the so-called "Leiden vessel", in which an electric charge could be stored. He thought that such a vessel could allow him to demonstrate that lightning was an electric phenomenon. During a heavy thunderstorm, he flew a kite that was linked to a Leiden vessel by a humid silk tow. The first stroke of lightning already electrically charged the vessel. This experiment inspired him to mount a steel wire as a lightning conductor on top of the St Paul's cathedral in London in 1769. Three years later, in 1772, the cathedral was hit by lightning and it was indeed observed that an electric current was flowing through the conductor, thus protecting the cathedral from damage. However, it was equally observed that the conductor became red hot at some places. The logical conclusion, taken by the crew, was to replace the steel conductor by a copper one. At that time, the famous Cambridge Physicist Henry Cavendish (1731-1810), had indeed shown that copper was a superior conductor compared to steel. Copper is even the second best metallic conductor, with silver being the best.

From that moment on, copper played a leading role in the further development of electrical engineering. Volta tested this metal for its performance as a battery material and towards the mid 19th century, copper entered the first electric machines –the dynamo, the electric generator, the electric motor and the transformer– as a conducting material.

The invention of the telegraph by William Cooke and Sir Charles Wheatstone in 1830, led to the first important application of electric copper cables. The first one was laid over land, namely from Euston to Chalk farm in London. But shortly thereafter the idea of laying a connection between Dover and Calais became reality. The latter undertaking had to be repeated three times before the right cable construction and a suitable isolation material was found. In 1861 the connection finally could be taken in operation.

As a result, the idea to connect the US with Europe with a telegraph cable gradually arose.
The transatlantic cable project has become one of the most heroic projects of modern engineering history, and one of the summits of technological progress in the nineteenth century. Again, several attempts to install the cable from especially designed and equipped ships –the Agamemnon and the Great Eastern (fig. 11)– failed.

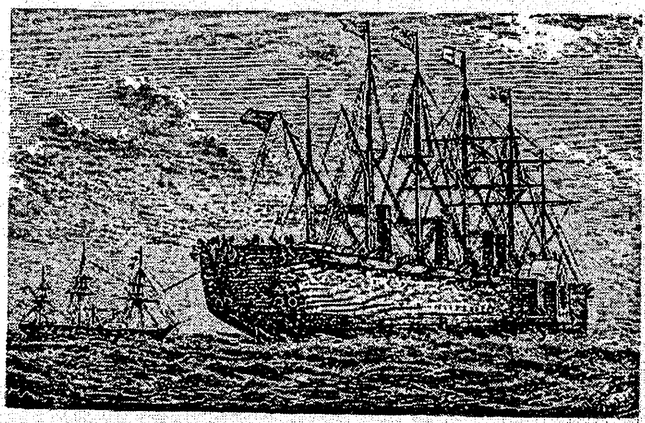

Fig. 11 : Artist's view of the Great Eastern, one of the two ships that laid the first transatlantic cable.

Again long discussion meetings followed about the optimal dimensions and design of the cable construction that would minimise the electric current losses over the 3700 km long distance between Nova Scotia and the isle of Valentia at the Irish coast. Finally, the engineers decided to take the advice of Sir William Thomson –the well-known Lord Kelvin– seriously, namely to make the cables from high-purity copper. Indeed, the first conductors had been purchased without any specification of conductivity, and one length of cable, made from arsenical copper from Rio Tinto was found to have only 14% of the expected conductivity[48]. This forced the copper producers to improve their production process in order to increase the purity of the material from 98% of that of "blister copper" to a purity of more than 99%[49]. Thus, the increased purity of copper substantially contributed to the successful completion of the Atlantic cable project in 1866. Thomson received a knighthood for his contribution.

New transmission lines for telegraph were laid in subsequent years over land as well as over sea. And with the invention of the telephone by Alexander Graham Bell in 1879 and the electrical distribution station in 1881, the demand for copper wire increased at a spectacular pace towards 2 million tons per year towards the end of the 19th century.

A consequence of this increased demand, copper mining started in Belgian Congo, Zambia and Chile: it was the beginning of the colonial part of modern metal history.

From Edison to Schockley

There are good reasons to call Thomas Edison the Leonardo da Vinci of Modern times. His 1093 patents indeed illustrate his enormous creativity[50]. There are, however, differences between both of them. Edison also made most of his inventions work, whereas Leonardo seems to have been satisfied

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[48] Cyril Stanley Smith "Metallurgy as a human experience" Metall. Trans. Vol 6A – (1975)

[49] Kelvin knew about the measurements of electrical resistivity of several metals by Henry Cavendish (1803), and his feeling that impurities or alloying elements could dramatically reduce that conductivity, was later confirmed by Matthiessen (1860).

[50] Kathleen McAuliffe "The undiscovered world of Thomas Edison" – Atlantic Monthly – 12 (1995)

with a number of nice sketches of numerous technical installations, before going back to work behind his painting easel or in his sculpture workshop. The two had creativity in common as well as the fact that neither one was a real scientist. Their main objective was creating, Leonardo on paper, Edison in reality. Neither was really interested in the fundamental mechanical or physical mechanisms behind their inventions.

Nevertheless, as far as Edison is concerned, there seems to be one exception. Amongst all his patents, one is related to the field of "pure science". Discovered in 1882 by William J. Hammer, a young engineer working in the Menlo Park laboratories[51], it became gradually known as the "Edison effect"[52-53]. Edison never applied the concept to one of his own inventions, but it was nevertheless an important finding. It anticipated the discovery of the electron as the carrier of electrical current by the British physicist, J.J. Thomson, in 1897. It thus became the basis of the vacuum electron tube and laid the foundation of the electronics industry.

The vacuum tubes were simple rectifier and amplifier devices that were state of the art of the electronics industry during the first decades of the 20th century. They were much more reliable than the elder point contact crystal rectifiers. With the advent of new communication equipment and radar, however, it appeared that the vacuum tubes were not suited for the high frequencies at which these devices had to work.
In the late thirties, a researcher in the Bell Laboratories, named Russel Ohl, still believed that there was a future for crystal devices. He was persuaded that these devices should become much more reliable if crystals of higher purity could be made. Not without trouble, he succeeded in persuading his boss Mervin Kelly to provide a budget for his research on silicon crystals. He soon could show that 99.8% pure crystals behaved much better as rectifier

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[51] One of the greatest accomplishments of Thomas Edison was the construction of the first industrial research laboratory in history, affectionately called by Edison "the invention factory", but more formally known as "the Menlo Park Laboratory" which would gradually evolve into the Bell Labs.

[52] When testing Edison's light bulbs, Hammer noted a blue glow around the positive pole and a blackening of the bulb at the negative pole. This was later explained by the thermo-ionic emission of electrons from the hot to the positively charged cold electrode.

[53] The phenomenon was first known as "Hammers phantom shadow", but when Edison patented the bulb, it became known as the "Edison effect".

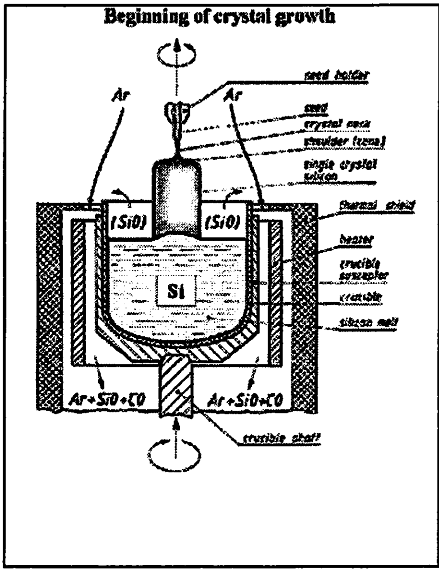
than its less pure predecessors. His most important finding took place on the 23rd February 1939, when he was comparing the amount of current travelling on both sides of a crack that went down the middle a silicon crystal. He then suddenly detected that the conductivity the crystal could be enhanced by holding it above some boiling water or underneath a strong shining light bulb.
He repeated the test in presence of his director Mervin Kelly and of Walter Brittain, a colleague recognised in the Bell labs as a most experienced experimentalist.
The light bulb test worked. There was instant surprise followed by weeks of reflection until it became clear what had happened. The crystal had different levels of impurities on either side of the crack. One side had, due to subtle traces of extra elements an excess of electrons – was n-type- , the other side a deficit –hence p-type-. Being in contact with each other a so-called "barrier" was formed at the tip of the crack. When electrons were mobilised by incident light, a current started to flow but the barrier only allowed it to move in one direction, namely from the n- to the p-side of the crystal.
The first p-n junction, the precursor of the solar cell, was born.

But the Bell labs and Melvin Kelly in particular were not so much interested in those days in the application of Ohl's crystals as solar cells, but in the idea that extremely pure crystals, doped in a controlled way by selected elements, might open the possibility of replacing vacuum tubes.
Kelly then decided to form a team of scientists with the goal to develop a semiconductor circuit that could replace the vacuum tube. Bill Schockley – a brilliant scientist- was appointed leader of the team. He, at his turn, selected the mentioned Walter Brattain and John Bardeen to be part of his crew. After several disappointing tests with silicon, the team decided to switch to germanium, which has the same structure as silicon. It was Gordon Teal, a crystal expert working in the shadow of the three "masters" of the Bell labs, had indeed succeeded to produce germanium single crystals with much higher purity than the silicon material Schockley's group was working on[54],[55]. Science historians mention the "exuberant parties and good lunches" during the seven year the team worked together; however, these years were

[54] G. Teal and J.B. Little "Growth of germanium single crystals" Phys. Rev. 78 (1950)647
[55] Germanium crystals can now be produced with only one impurity element for every 10^{12} atoms.

not free of tensions, due to competition or disagreement, apparently often induced by the obstinate character of Schockley.

Anyhow, the 30th of June 1948, the Bell Labs could present the first germanium transistor to the press. And in 1956, Schockley, Bardeen and Brittain received the Nobel Prize in physics.



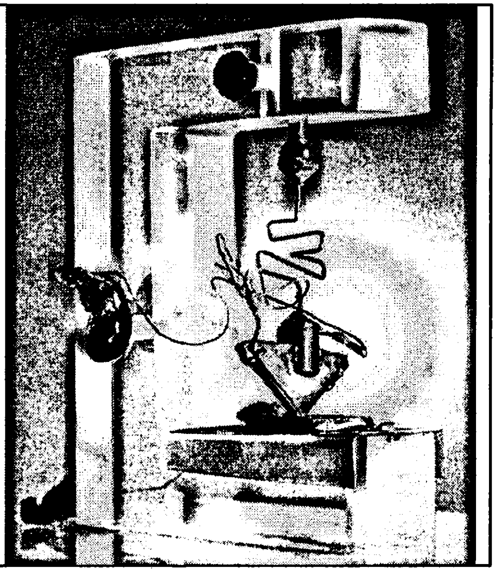


Fig. 12 : The Czochralski method of crystal growth.
Essentially a crystal is "pulled" out of a vessel containing liquid Si by dipping a "seed crystal" into the liquid, which is subsequently withdrawn at a surface temperature of the melt just above the melting point. Traces of impurities remain in the melt.

Copy of the primitive first transistor made by the Schockley, Bardeen, Brittain team.

After his success with germanium, Gordon Teal had continued research on silicon crystals and tried to improve their purity by applying the crystal

growing Czochralski method[56]. He was discovered by Texas Instruments, who persuaded him to join their company. A few years later, in 1954 TI could unveil the first silicon transistor. Silicon is not only much cheaper but it has a number of operational advantages[57] over Germanium.
Four weeks after the presentation of Gordon Teal's transistor, the first silicon triodes were in production.

In the meantime, Schockley had left the Bell Labs to create Schockley Semiconductor in Palo Alto, California. There, he also attracted top-engineers and physicists, however not for a long time, since similar conflicts as before arose in Schockley's team. For similar reasons, eight people left the company to create Fairchild Semiconductors. Two of these eight, namely Bob Nyce and Gordon Moore founded Intel Corporation. Together with the Texas Instruments labs, Intel laid the foundation of the integrated circuit allowing millions of transistors and other electronic components to be grafted on a centimetre-size silicon wafer. It was the opening of the ICT era and the start of the Information Society.

SUMMARY AND CONCLUDING REMARKS

Metallurgy and History

Starting from the chalcolithic period, the development of new metallic materials and metallurgical processes had a decisive influence on the history of technology and even on the course of European –Western- history. The transition from stone to Copper brought the early settlers in contact with totally new materials with hitherto unknown properties: it was the start of numerous new crafts and a continuously expanding variety of metallic tools, weapons and systems.
Gold extended the duration of Pharaonic Egypt, it was the ideal instrument for Mediterranean people to change from barter to monetary trade, and it underlined the power of Thracian warlords and Celtic Oppida leaders. The Laurion Silver lode provided the visionary Themistocles the means to put the Athenians at work to build a powerful navy that for once and forever freed

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[56] G. Teal and J.B. Little "Growth of germanium single crystals" Phys. Rev. 78 (1950)647

[57] For some applications, germanium has a better performance than silicon, e.g. for satellite solar cells.

Europe from Persian occupation, thus paving the path for Classical Greece to develop into the cradle of Western Civilisation. The Bronzes were the first really technical metallic materials, much wanted by the farmer and the soldier, and, because of the relative scarcity of tin and copper deposits, gave a great stimulus to the development of trade over land and over sea in Western Europe and the Mediterranean.
Once metallurgists succeeded in controlling the Hittite sponge iron or bloomery process, and because of the abundance of iron ore, steel gradually took over the role of the bronzes and intruded agricultural, military and civil engineering workshops from southern till northern Europe. The quality of iron and steel tools and weapons played a decisive role in the development of agriculture and sometimes also in the outcome of wars. When after nearly 3000 years of iron metallurgy, western European metalworkers were able to heat their high furnaces to the point of making liquid pig iron and later on capable to transform that pig iron into different steel qualities, the first signal of the looming industrial revolution was given.
Steelmaking know-how was transferred first from Wallony to Sweden and later from Great Britain to the continent. It was a dynamic movement of industrial and economic centres of gravity over Europe, taking place in the stimulating atmosphere of the Enlightenment. In that same period of Enlightenment, new elements of the Periodic Table were discovered one after the other, one of the most important being Aluminium. Barely fifty years later, strong aluminium alloys gave a great impetus to the development of today's civil air transport.
Scientists and engineers from the early twentieth century then laid the foundation for a metals and materials science, which is expanding into several high-tech developments of the new millennium. The article closes with the story of the first transatlantic cable and that of the first transistor. In both cases, the improved purity of the material –copper viz. silicon– allowed a breakthrough towards the development of modern information and communication technology.

Metal Properties and History

Behind the successive stories of the present paper, covering eight millennia of human history, the application of always new properties of metals is hidden. For the physical explanation of these properties and their relation to structure and process conditions, one had to wait for the development of metal science which took place during the twentieth century.

The first property was the one that distinguishes metals most from stone materials like flint and other quartz varieties: the possibility of bending and forging them without rupture, revealing the potential of *plastic deformation*. It is this property that opened the metal age, the chalcolithic hinge. The discovery that these materials were harder after than before hammering soon followed. This phenomenon is called *strain hardening*. The observation that a strain hardened implement, having been dropped in a fire, regains its original softness faced metal workers with the mechanism of *recrystallisation*.

The value of the noble metals gold and silver was not only determined by scarcity and precious colour but even more by their durability thanks to their *oxidation and corrosion resistance*. *Alloy hardening* –mainly by solid solution strengthening– was the physical base for the success story of the bronzes. *Allotropic phase changes of iron* and the specific pattern of the *iron-carbon phase diagram* allowed for a multiplicity of thermal treatments, fiddling microstructure and properties of steel and cast iron, thus widening the applications of the iron-based materials for engineers, farmers and warlords. The *thermodynamics and kinetics* of reactions in smelting and melting furnaces can a.o. explain the progress that was made by the introduction of the Walloon furnace, and the metallurgical contributions to the industrial revolution namely the coke fired blast furnace and subsequent refining technologies.

The development of *precipitation hardening* treatment is the base of the successful introduction of aluminium in airplane construction whereas the influence of impurities and lattice defects on the *electrical conductivity* of copper and on the performance of the semimetals germanium and silicon as *semiconductor* materials scientifically explain the recent ICT hinge of human history.

It was mentioned earlier that the blacksmiths of classical times were persuaded that keeping an iron dagger or knife in contact with a hot charcoal fire for a sufficiently long time, was a process of purification. Many other explanations of the effect of alloy additions and thermal or mechanical treatments on the properties of metallic materials were interlarded with mythical stories and superstition –like the story of William Gilbert, discussing the influence of garlic on the working of the compass needle–.

Though superstitious thoughts disappeared with time, we had to wait till the late nineteenth century before scientists started to suspect that differences in properties between metals and alloys were not only due to differences in chemical composition but also to differences in structure.

The allotropy of iron was proposed around the turn of that century as being "different molecular states of iron" [58,59] and attempts were made to relate the hardening of steel to the existence of these two phases[60]. It is surprising to hear that several steel varieties –tool steels and even stainless steel– and aluminium alloys were developed before the crystal lattice structures of iron and aluminium were known. Harry Brearly, one of the inventors of stainless steel once said: "at the best, metallurgical science hitherto was able to explain what the metalworkers already knew for a long time." And Henry Clifton Sorby, an English geologist, who is generally recognised as the first who used a microscope to study the structure of metals, referring to the situation around 1870 wrote: "In those early days, if a railway accident had occurred and I had suggested the company to take up the rail and have it examined with a microscope, I would have been looked upon as a fit man to send to an asylum."[61]

In every case, even up to the middle of the twentieth century, practice in metallurgy was far ahead of metal science. Only in the early decades of that century, the crystalline nature of metals could be experimentally proved by X-ray diffraction. From then on, the nature of different phases in metallic alloys started to be revealed.
The development of always more advanced investigation techniques, together with numerous successful efforts to model processing-structure-property relations speeded up the development of all fields of metal science. Nowadays, metal and metallurgical sciences have become indispensable instruments of innovation in the metallurgical technology of today.

Moreover, the evolving metal science also laid the foundation of a much broader materials science and engineering. This reflects –as will be shown– a "materials hinge" of historical importance, namely the end of the domination of metals in the materials world of the early third millennium.

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[58] " Théorie cellulaire des propriétés de l'acier" F.Osmond and F.S. Werth – Annales des Mines 8,5, (1885) and Mémorial de l'Artillerie de la Marine » 15, 225, (1885)
[59] " On the Manufacture of steel armour-penetrating shells" (in Russian). D.K. Tschernoff- Notes of the Russian Engineering Society 6, 83, (1885) Quoted by V.D. Sadovsky in
[60] The Sorby Centennial Symposium on the History of Metallurgy" – ed. C.S. Smith – Gordon and Breach science publishers – (1965)
[61] "Sorby: the Father of Microscopical Petrography" – D.W. Humphries in [3]

The end of the domination of metals

Starting from the 17th-18th century, the centuries of Enlightenment, history became more personalised, also outside the field of religion and philosophy and of political and military power. The conviction that men could understand creation and dominate the world became widespread. Therefore, science and scientists entered the spotlights. Gradually, chemistry started to leave the crypts of alchemy and delivered hard scientific matter. Between 1750 and the end of the 19th century, the number of known elements increased to a multiple of those that men had succeeded to isolate in the millennia before[62].
Many of them have become of great importance in our technological world, not only as an alloying element of the base metals but also as an individual element in numerous applications: zirconium in nuclear power plants, titanium in medicine, petro-chemistry and aerospace, germanium in satellite solar cells etc.

However, besides metallic materials, new very-promising families of non-metallic materials appeared, first at a low but in the second half of the 20th century at increasing pace. These are the man-made polymers, the technical ceramics and a great variety of composite materials. They not only opened a whole world of new applications, but also increasingly act as competing materials or even as substitute for metals and metallic alloys. Progress in the metal field continues, but we have to recognise that we entered an era, in which the four material families –ceramics, metals, polymers and composite materials– have attained equal importance for shaping the future technological world.

Beware of Euro-centrism

Nearly three millennia ago, in the Lake Superior region in North America, a huge deposit of native copper was exploited by the local Indians. The metal was squeezed out of the rocks by hammering and subsequently used in its

[62] Nickel (1751), Manganese (1774), Cobalt (1780), Tellurium (1782), Titanium (1795), Niobium (1801), Palladium (1803), Rhodium (1804), Magnesium (1808), Cadmium and Selenium (1817), Zirconium (1821), Aluminium (1825), Silicon (1854), Thallium (1861), Indium (1863), Gallium (1875), Germanium), (1886), Beryllium (1898).

native state, not only for a variety of ornaments, but also for tools, utensils and weapons. Pre-Columbian Indians thus equally had their Chalcolithic hinge.

In South-America, in the so-called "Antiplano" of Bolivia and Southern Peru, the start of a settled village agriculture stimulated the development of smelting processes: remnants of mining sites learn that Copper extraction metallurgy was known from at least 2000 B.C. whereas the oldest known copper objects stem from 1200 B.C. [63]. The technique of copper smelting used by the Incas and described by the Spanish conquistadores –several men rhythmically blowing through tubes into a heap of intermingled malachite ore and burning charcoal– probably did not differ much from the smelting techniques used in Eurasia several millennia earlier. In Peru, arsenic-bronze was discovered between 200 and 600 A.D., and remained the alloy of choice until tin-bronze became the official standard after the formation of the Inca state about 1470[64]. Furthermore, we should not forget the advanced metallurgy and especially the special surface technologies developed by the Incas to extract the copper atoms from the surface of gold-copper ornaments, leaving the impression of pure gold [65].

As important, if not more, are the metal hinges in the history of East Asian countries. The Bronze Age and bronze trade developed during the same era as in the times of the Celts and the Thraciëns in Europe, hence before classical Greece and Rome; their influence on the history of China, India, Vietnam ... attracts increasing interest of archaeologists. It is an established fact that the copper-zinc alloy brass was developed in India and that the condensation process of zinc extraction also was an Indian invention.

Cast iron metallurgy was developed in China from around 500 B.C. and had an enormous influence on Chinese agriculture, shipbuilding and military

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[63] "A concise history of Bolivia" Herbert S. Klein, Cambridge University Press 2003

[64] CATHRO, R.J., 2000. The history of mining and metallurgy in Latin America, 1500 BC–1600 AD. In Volcanogenic Massive Sulphide Deposits of Latin America. Edited by R.L. Sherlock and M.A.V.. Logan. Geological Association of Canada, Mineral Deposits Division Special Publication No. 2, p. 2-3

[65] Noble metals were, however, so abundant in the Inca Empire that the population attached more importance to a nicely woven carpet than to a golden statue, they detected the value of their precious metals only when the Conquistadores started to disintegrate their Empire mainly for its gold and silver riches.

infrastructure till 1500 A.C., when a mysterious decline occurred. The western world on the other hand had to wait another three centuries before cast iron metallurgy started to reach technological maturity.
Therefore, the present article was consciously focussed on metallic hinges in *Western* History. These are only part of the metallic hinges in World History. Even in the field of the history of metals, we should beware of Euro-centrism.

Innovation: lessons from history

An obvious question of today's researchers is how, all along human history, people came to new metallic materials and how to the development of new metallurgical processes. Was it always necessity that spurred the inventive efforts? Was it always market pull?
No, it was not. Copper metallurgy was not developed because there was a shortage of stones. It was developed because craftsmen and artists, surprised by the red drops on a furnace wall and the peculiar malleability of these drops, made an ornament of them, before others became aware that the material opened a number of new, interesting and useful applications. In a similar way, we could state that today's need for automobiles and trucks arose *after*, not before, they were invented.
Thus, necessity and utility solely cannot account for the variety and novelty of the artefacts created by humankind; we must seek other explanations[66].
Cyril Stanley Smith[67] stated, "Discovery is less likely to occur when people are desperately earnest, than when they are in a sensitive, somewhat playful mood. The artist's sensitivity to colour and texture naturally brings him into contact with more properties of materials than are encountered by the maker of useful objects".
Very often indeed, the curiosity of the craftsman has been a much greater stimulus to inventions than the "animal need". This explains why most of metallurgy, both alloying and heat treatment, as well as mechanical shaping often first called attention from art, fashion and ceremonial events.
It teaches us that freedom of research, pleasure in beauty and unexpected properties, and entrepreneurial open-minded curiosity are ingredients of utmost importance for an academic research team.

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[66] "The evolution of Technology" –George Basalla – Cambridge History of Science Series- Cambridge University Press – 1988
[67] C.S. Smith "Metallurgy as a human experience" – Metall. Trans. Vol. 6A – apr. 1975

Secondly, "invention" is often better defined as "innovation", because it is the result of combining existing and known elements in order to "invent" a new element. All along history, up to the present day, technological change was not accomplished by a series of great unrelated leaps forward by a few heroic inventors. Instead, the form of a "new" or "modified" artefact was mostly based on that of pre-existing predecessors, and it is very often true in the development chain of new materials and processes, links of "creative copying" have been of vital importance.
It was mentioned earlier how the names of scientists and inventors entered the spotlights since the Enlightenment. This can, dangerously, lead to a heroic theory of invention, in which previous small improvements in technology, leading to the invention, are ignored and all emphasis is laid upon the individuals that made the final major breakthrough. The lost wax metallurgy for the bronzes is said to have been developed in Egypt, but who knows what the Egyptians had learned from previous trials in Mesopotamia and farther East? Darby I is recognised as the father of the coke blast furnace, but his development was based on the experience of malt-making shops and on the less successful experiments of others with coal. And although Russel Ohl and Gordon Teal made fundamental discoveries, leading to the development of the –of course more revolutionary– transistor, their contribution to the production of ultra-pure semiconductor crystals and to the invention of the semiconductor junction has been largely forgotten[68] .

Finally, even in today's high-tech world, basic principles are in many cases derived from practical experiments, often by chance, thus reversing the orthodox concept of pure research leading to applied research. Hence, formally trained scientists, though their contribution to metals science and to the development of new metallic materials has to be recognised – and becomes of increasing importance- should never depreciate the engineering contribution to a world, hitherto largely shaped by the history of metals.

68 http://www.ieee-virtual-museum.org