Chapter-1

Introduction

1.1. Introduction

Soldering is the process of melting solder around a connection to combine two or more electrical/electronic components by pouring the filler metal inside the joint. Generally, the melting point of filler metal is lower than the adjoining metal. Unlike welding, the work parts don't melt in the process of soldering. Soldering differs from brazing with respect to the melting temperature of brazing which is performed at a temperature higher than soldering without melting the work piece. A permanent bond between solder and work piece is formed in soldering that cannot be broken using a de-soldering tool. They provide both electrical and mechanical support, and solder alloys are very extensively used as the linking material in electronic industries for packaging. Most of the solder alloys are basically tin-based. Tin and lead (Sn63/Pb37) alloys are a good combination for soldering material due to their eutectic or near eutectic temperature, low around 183˚C, good mechanical and electrical properties, low cost, and Physico-chemical properties [1][2][3].

Despite these benefits, there is a significant disadvantage of heavy metals like lead due to its toxicity. Now, a lot of efforts have been made in recent decades to restrict its use as it could pose an immediate risk to human health and the environment [4][5]. In many European countries and many countries across the world, Pb was banned in paints, fuels, and plumbing applications. Since many countries have come up with very stringent legislation that mandated the limitation of the use of certain hazardous substances (RoHS)[6] and the waste electrical and electronic equipment (WEEE)[7], the alloy design and development and process design of the soldering made a substantial shift in direction. The European Union was the first administrative territory to come up with stringent policies against Pb usage in electronics, enacting the RoHS and WEEE rules. These restrictions have been imposed to control the use of lead in fast-growing electrical and electronic equipment. All these measures are taken to reduce the use of various dangerous substances. It is the manufacturer's responsibility to dispose-off safely or recycling of this waste after the end of their useful life. It has been seen that Pb and Pb-containing compounds hold an important place among the top 17 pollutants, which are direct threats to human life and the environment, according to the US Environmental Protection Agency (EPA). The use of lead (Pb) in flame retardants has been phased out under the "Directive on the Restriction of Hazardous Substances in Electrical and Electronic Equipment since, July 1, 2006, in Europe" As a result, researchers have started looking for new alternative solder that is free of lead without compromising its properties [8][9]. It has been one of the most critical challenges in the electronic packaging and manufacturing sectors. Before recommending a new lead-free solder, it is essential to critically evaluate the important properties like liquidus temperature, mechanical performance, microstructure, wetting behaviour, corrosion behaviour, pasty range, solderability, dependability, etc. [10][11]. The cost and reliability of the solder must be considered while producing a new solder. The conventional lead-tin solder has been in use for many decades, and many engineering designs are based on the properties of existing solder alloys. If the characteristics of the solder alloys change, then the changes in design have to be made, which is not that easy. Therefore, developing lead-free solder alloys with similar properties to conventional lead-tin solder is a great challenge. For example, any increase in the melting temperature at which printed circuit boards (PCBs) are processed has a negative impact on component dependability. Due to the limited melting point range, a study is limited to a few different alloys based on Sn with added elements. In addition to the temperature requirements, Sn-Pb has some metallurgical and mechanical qualities that an alternative alloy must match to be a viable replacement.

1.2 History of Solder

Soldering is a well-known method for joining materials. Many people might be unaware that soldering has been used for thousands of years. The importance of joining for creating tools and making ornaments purposes led to discovering a primitive kind of soldering. Metal joining for making tools and other materials was a necessity. Ornaments have been important since ancient times, and people were often buried with their most delicate jewelry. The burial grounds were preserved, cared and well maintained because they were considered sacred places. According to history, soldering was first practiced in Mesopotamia some 5000 years ago [12]. This confirms that the ancient Egyptian goldsmiths knew how to combine gold more than 5000 years ago. Soldering is used to make the legendary Sumerian swords. Soldering was used to build jewelry and cooking items in ancient times. Since then, soldering technology has advanced rapidly around the world. The ancient Romans achieved the incredible feat when they soldered 400 kilometers of lead-based water pipelines.

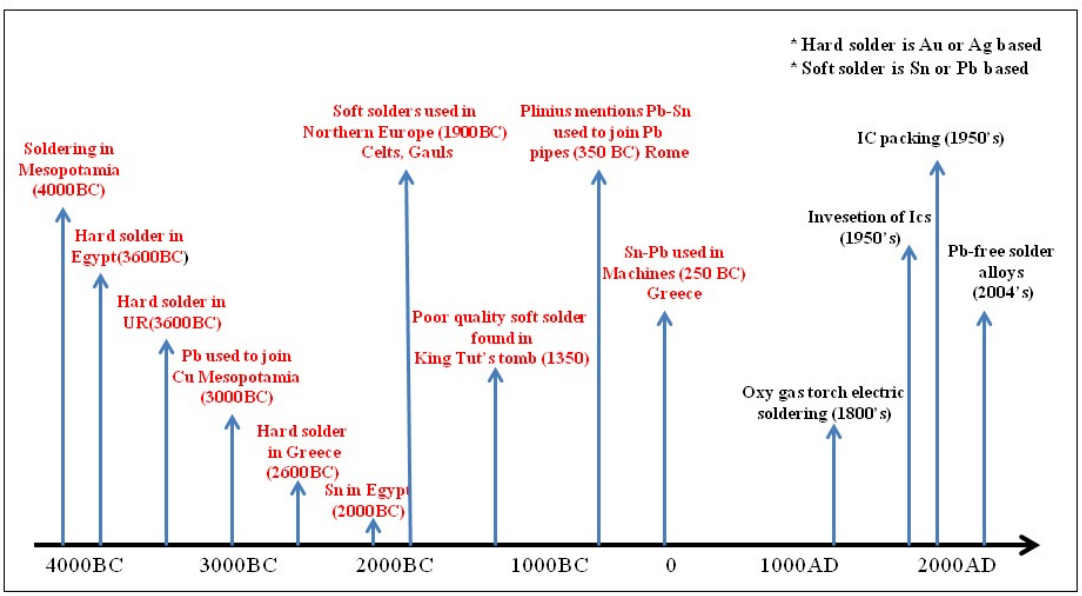


Fig.1.1 **History of use of solder** [13]

Tin-lead soft solder compositions and their uses by ancient people were unknown. Furthermore, Enslaved artisans used to carry out the soldering process, because of which there were no written documents available about the soldering. The higher ruling class did not consider such attempts essential and not adequately documented. In King Tut's tomb, in the year 1350 BC, some soft-soldered objects were found. Hard soldering techniques were well developed than soft soldering in Mediterranean cultures. Historians currently assume that Celts and Gauls invented soft soldering in Northern and Central Europe around 1900 BC. In ancient times, tin-lead solders were utilized mainly in constructing and repairing cooking utensils and metal implements. The Greeks used tin-lead alloys to protect their bronze-based water pumps, air pumps, and organs circa 350 BC. Tin-lead soldiers were widely utilized by the Romans in the construction of aqueducts. Soft soldering was used to attach the lead sheets lining the water tunnels' interior. The higher cost of tin compared to lead gave the Roman engineers economic incentives to adopt the less expensive tin-lead alloys, just as it does today. From the Iron Age to the Middle Ages, soldering hardly changed. Artisans typically used the method in the creation of jewelry and other crafts. Solders containing tin and lead were used to join copper and brass objects. Soldering technology was dramatically expanded throughout the Industrial Revolution. Soldering first appeared in the electronics sector in the early twentieth century as a dependable method of connecting copper wires for power and signal transmission. In those early applications, the solder joint's primary purpose was to ensure electrical continuity.

However, with decreasing package sizes, these industries expect solder alloys having good mechanical properties like a creep, fatigue resistance, and strength apart from the lead-tin soldiers' mechanical and electrical interconnection ability. The limits of tin-lead solder technology were vividly demonstrated by introducing surface-mount technology. It was seen that many times the solder fails first, followed by the device failure, which put many questions on the reliability of the solder alloys. At the same time, materials scientists were looking for a solder having better mechanical strength and reliability that could replace lead-tin alloy. Further, it was realized that the lead needs to be replaced in solder alloy due to its toxicity. Therefore, it is essential to remember that the need for a lead-free solder alloy was not only a technological requirement but also a protection of environmental and health concerns. However, in the light of growing environmental and health concerns, the materials science community should carefully look for various new options. Since lead has all the excellent properties except toxicity, it is not easy to successfully replace lead in tin-lead solder.

1.3 Types of Soldering

Soldering is the method of joining two or more metals by pouring a filler metal into the joint without melting the substrate below the temperature of 450°C. Solder means a group of metals or alloys with a low melting temperature used to fuse even two dissimilar metals. The distinction between soldering and brazing is made based on the temperature at which the processes are carried out. It is considered that the soldering is carried out below 450°C. The filler metal used in soldering first occupy in the joint by capillary action and then freezes to give a permanent joint in contrast to welding in which the base metals are also melted. In soldering, the Sn and Pb alloy system are the most popular. Their relative proportions in a binary alloy can be adjusted to produce melting points as high as 327.5^{0}C for pure Pb, although the eutectic point is 63Sn/37Pb. This eutectic combination melts quickly at 183°C and is widely used to join wires and components in electronic circuits and assemblies, either manually or automatically.

There are three different methods of soldering, each of which uses greater temperatures to generate stronger joints:

- **Soft soldering (90°C-450°C):** This technique has the lowest melting point with a filler metal melting temperature of less than 400°C. These filler metals are generally alloys, with liquids below 350°C and often incorporating lead. Because of the low temperatures utilized, soft soldering thermally strains components the least but does not form strong junctions, making it unsuitable for mechanical load-bearing applications. This solder also loses strength and melts at high temperatures, making it unsuitable for usage.
- **Hard (silver) soldering (temperatures above 450°C):** The bonding metal in this procedure is brass or silver, and it takes a blowtorch to reach the temperatures at which the solder metals melt.

- **Brazing (>450°C):** A metal with a substantially greater melting point than those used in hard and soft soldering is utilized in this soldering method. However, unlike hard soldering, the metal to be connected is heated rather than melted. Once both materials are sufficiently heated, the soldering metal may be placed between them to melt and function as a bonding agent.

1.4 Soldering Material

Solder alloys are used to solder linkages in a variety of ways. Tin (Sn) alloys with one or more of the following elements are used to make these solders alloys [14]: Lead (Pb), Bismuth (Bi), Indium (In), Silver (Ag), aluminum (Al), Antimony (Sb), Chromium (Cr), Cadmium (Cd), Zinc (Zn), Copper (Cu), Nickel (Ni), and other metals are examples. A solder alloy is considered eutectic if the solidus and liquids temperatures are the same; otherwise, it is called non-eutectic. Commercially available solder alloys come in solid, paste, or powder forms.

1.5 Soldering Method

Soldering is a metallurgical process combining two or more metals by melting the solder alloys between the joining metals. There are mainly three methods used for soldering.

1.5.1 Reflow Soldering

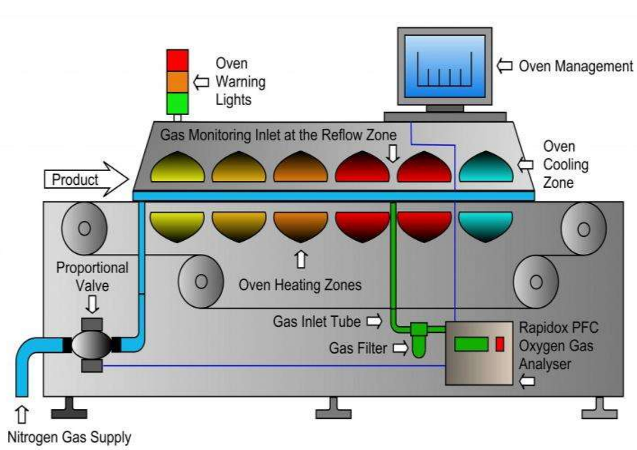
Nowadays, thinking of life without phones, tablets, or computers is difficult. It's not surprising that in a world with more gadgets than people, electronics have gradually become an indispensable aspect of modern life. The demand for gadgets is increasing daily, and the expectations of the consumers and industries are also increasing for good quality and reliability[15].

A PCB can be found inside various gadgets (printed circuit boards.) PCB manufacturers all over the world are constantly putting effort into improving quality control to reduce product failure. The reflow soldering process is the most preferred manufacturing method for many PCB makers since it enables for mass production of PCBs with complicated surface mount component soldering of the highest quality.

The reflow soldering procedure uses a solder paste to temporarily attach multiple electrical components to their contacts on the circuit board; following assembly, the solder is melted, and the junction between the component and the circuit board is permanently connected. Nitrogen is added to the solder reflow oven to improve soldering quality by creating an inert atmosphere that reduces the danger of oxidation and improves the wetting angles of soldered junctions. A gas analyzer capable of monitoring oxygen content ppm (parts per million) is used to maintain the oven's inert environment.

Reflow Soldering Process

Preheating → Thermal Soak → Reflow Soldering → Cooling



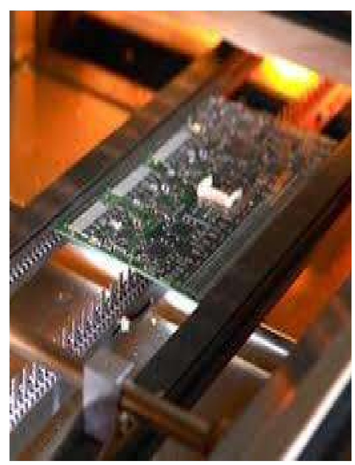


Fig.1.2 Reflow soldering Process

1.5.2 Wave Soldering

Wave soldering is slightly different from reflow soldering. A continuous wave of solders is passed over a printed circuit board (PCB) assembly. The exposed metallization of the assembly is touched and moistened by the crest of the liquid solder wave, and solder joints develop as it cools[16].

The following steps are followed in wave soldering:

1. Through-hole component leads are automatically inserted into holes in the printed circuit board (PCB).

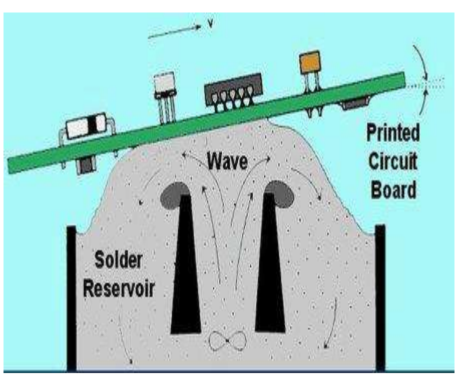
2. Adhesives are dispensed at areas on the PCB where surface mount components will be installed.

3. Attaching surface mount components to the glue that has been dispensed.

4. Adhesive curing forms a temporary bond that allows components to be hung beneath the circuit board. The wettability of the solder, the type of flux, the solder bath temperature, and the soldering dwell time all affect the success and dependability of the wave soldered junction

Wave soldering Process

Flux spraying → Preheating → Wave Soldering → Cooling



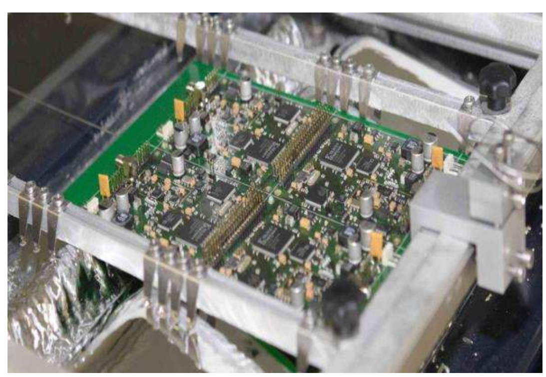


Fig.1.3 Wave soldering Process

1.5.3 Hand Soldering

The most popular and easy soldering process is Hand soldering in the electronic industries. The energy required to heat the pieces to be joined and melt the solder is transferred by exerting pressure with a soldering iron's pre-tinned soldering tip. Soft soldering is another name for this technology. Manually or automatically, the soldering iron can be steered. The pre-tinned tip of the soldering iron is placed above the joint and pressed against the joining partner to heat it. Following that, a certain amount of solder wire is introduced to the solder connection, where it fuses and melts. The solder junction solidifies once the soldering iron is removed.

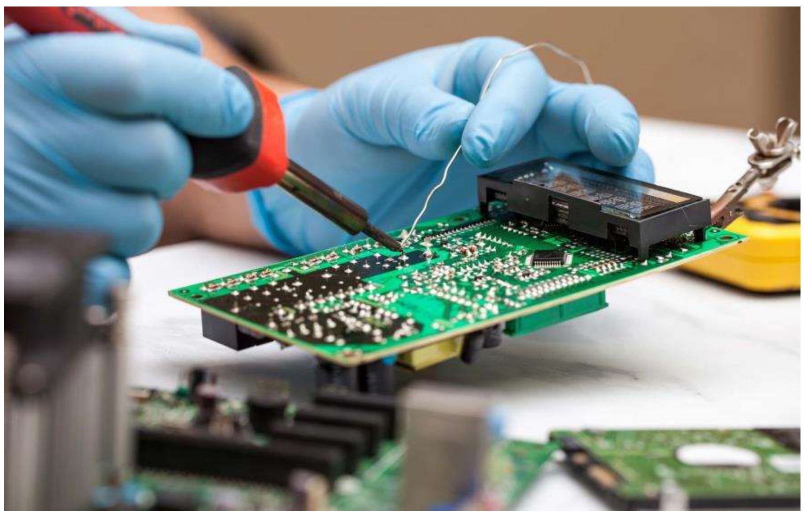


Fig.1.4 Hand soldering Process

1.6 Electronic Packing

Electronic packaging refers to enclosing, protection from damages, and providing physical support to electronic devices, components, and assemblies. Electronic devices have become more complex recently, requiring more resistors, transistors, and diodes on a single semiconductor chip. These discrete circuit components are integrated into or on the chip and wired to the printed circuit board (PCB). Interconnections for all of these tiny components can be established using various methods. A significant quantity of heat is generated when the device is in use, evacuating for the gadget to function correctly. Semiconductor chips are delicate and require a protective 'armor' layer to shield them from chemical, mechanical, and environmental harm. As a result, the term "electronic packaging" has been used to define the manufacturing process or the hardware that provides electrical connections, heat dissipation, and environmental protection[17].

1.7 Application

The electronic packaging assemblies are used in the following areas:

- **Computers and Business Equipment: D**esktop computers, laptops, high-performance computers, printers, calculators, personal digital assistants, photocopiers, etc.
- **Consumer Electronics:** VCR and CD players, watches, portable and compact audio players systems, microwaves, fridges, washing machines, ovens, TV sets, mixier grander and video game systems, etc.
- **Communications:** Telephone, smartphones, Modem, network card, Bluetooth and wifi devices, routers and fax machines, etc.
- **Industrial and medical systems:** Motor and process controls, Test and measuring devices, uninterruptible power systems, robotics, calibrators, NC controls, implants, medical imaging systems, etc.
- **Automotive Electronics:** Turbocharger control, cooling system, throttle, and Fuel injection rate control, Anti-lock braking, electronic brake-force distribution, electronic differential slippery, parkin assistance, speed assist system, automatic wipers and cooling, and navigation system, etc.

- **Military Electronics:** High-frequency and land mobile radio, missiles, avionics subsystems, Military neck microphones, satellite navigation systems, land-based radar, and communication systems.

Fig.1.5 Application of solder

1.8 Issue with lead-based solder alloys

1.8.1 Lead Poisoning

Environmental Protection Agency (EPA) prepared a list of polluting hazardous substances that harm human life and the environment. The pure metal lead and its compound are placed at the 17^{th} position in that list. The Pb has a greater tendency to bind the protein in the body and affects normal functioning. This is the main reason for lead poisoning when the lead concentration is high in the blood. It also affects the Ca and vitamin D metabolism[18][19][20]. Plumbism is another name for Pb toxicity. Pb oxide paint is also toxic, putting youngsters at greater risk than adults. According to the World Health Organization (WHO) and the US Centers for Disease Control and Prevention, blood lead levels of more than for adults 10 µg/dl and 3.5 µg/dl for children, respectively, and scan slow tissue development[21][22][23].

1.8.2 Adverse Effects of Pb On Human Life

Lead poisoning affects a wide range of physiological functions and organs. When a person is exposed to Pb, they may experience the following symptoms:

- **Immediate Effects**
    - Diarrhea, convulsions, vomiting, etc.
    - Abdominal pain, appetite loss, Constipation, etc.
    - Irritability, sleeplessness, headache, etc.
- **Ultimate Effects**
    - Continual exposure to Pb can harm the kidneys, liver, and brain.
    - Pb is the cause of osteoporosis (a disease that makes bone brittle)
    - Excessive Pb exposure can result in convulsions, mental retardation, behavioral abnormalities, anemia, and high blood pressure, among other things.
    - Pb can damage the placenta and the unborn child during pregnancy.
    - Female employees exposed to high levels of Pb may experience miscarriages and stillbirths.
    - Infants' intellectual development, behavior, stature, and hearing can all be harmed by a modest quantity of Pb.

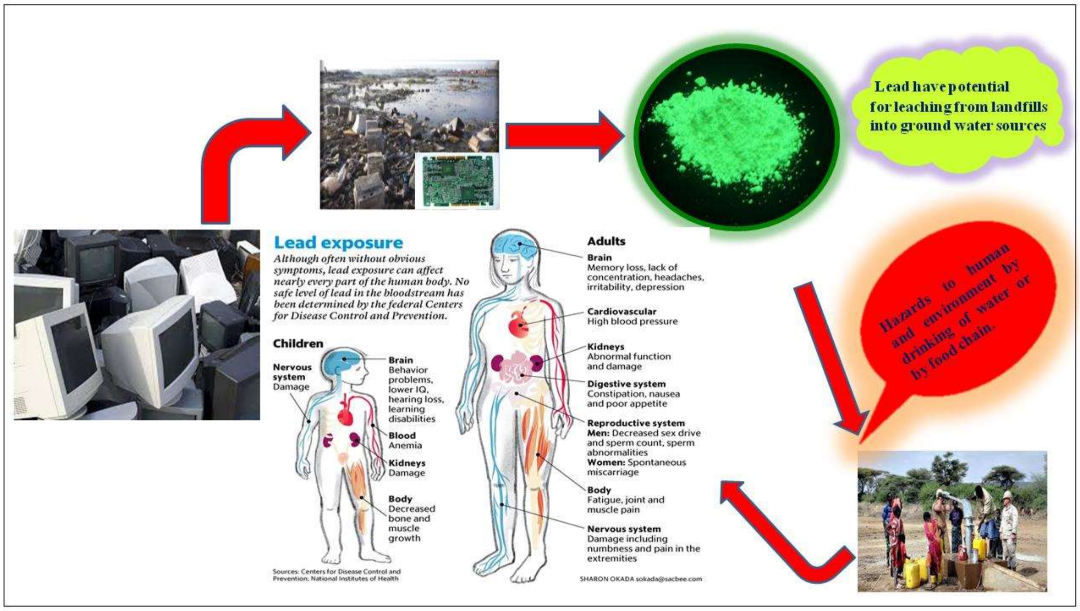


Fig.1.6 Effect of lead

1.8.3 Adverse Effects Of Pb on Environment And Other Species

Electronic industries generate a large amount of waste because of the quick expiry of electronic gadgets. These components are disposed of in solid waste dumps. The lead from the landfills gets leached, joins the groundwater, and becomes polluted. The standard filtration procedure we employ to clean water is insufficient to remove Pb effectively. The bonding of lead forms with water is difficult to break and remove by filtration. Japan and the United States are the two largest suppliers and users of printed circuit board assemblies. It is expected that this market will increase in the next ten years. Therefore effective Pb disposal would be a bigger problem in the future. Though recycling Pb can solve the above problem, there are certain drawbacks[24][25]. The performance of recycled lead used in the solder is not that good due to the high emission of lead particles. Growing industrialization is also another reason for the increasing level of lead in the environment. India's water bodies have been contaminated with significant levels of Pb. Water containing 0.003 mg/l of Pb is considered an average level of Pb [26].

Lead is also found in soil as soluble and insoluble organic salts that readily interact with colloidal organic molecules. Pb toxicity in plants is primarily caused via absorption, transport, and intracellular localization. When Pb reacts with a collection of enzymes, it causes them to slow down. Pb poisoning affects animals with symptoms similar to those experienced by humans, such as gastrointestinal pain, peripheral neuropathy, and behavioral abnormalities. Pb bullets are commonly used for hunting wild animals, and if predators devour these killed animals, they are in jeopardy. As a result, Pb shots have been outlawed in countries like the United States and Canada[27][26].

Accidental Cases

- Lead poisoning in Nigeria killed around 400 children in Nigeria on October 5, 2010 (Zamafara state Pb poisoning pandemic)[28].
- More than 1000 youngsters from ten separate villages in China were found to have high levels of lead in their blood near the Yuguang gold and lead-smelting factory. Following the event, 15000 people relocated from the area, and the government halted Pb production at 32 factories[29].

1.9 Source of exposure of lead

Pb can be found in a variety of places in the environment. The following are the most common:

- **Electronic waste:** The main reasons for the exponential growth of the electrical and electronic industries are increased demand and the quick expiry of gadgets. As a result, a massive quantity of waste is generated [30][31]. Electronic and electrical waste (e-waste) is defined as "waste electrical or electronic equipment, including all components, subassemblies, and consumables that are part of the equipment at the time of waste." Globally, 53.6 million metric tons (Mt) of e-waste were produced in

2019, according to the Global E-waste Monitor. By 2030, this quantity is expected to rise to 747 Mt. Asia (24.9Mt) produced the most e-waste in 2019, followed by the Americas (13.1 Mt), Europe (12 Mt), Africa (2.9 Mt), and Oceania (0.7 Mt). An estimated 80% of e-waste from industrialized countries is illegally shipped to LMICs such as China, India, Nigeria, Brazil, Ghana, and Pakistan, where labor costs and disposal are low, and restrictions are lax or non-existent[32].

- **Drinking Water:** The primary sources of Pb in drinking water are lead-containing pipes, faucets, and Pb-containing solder used during pipe repairs. Groundwater pollution occurs by leaching the Pb from the waste landfills. Pb dissolution in water is affected by the acidity of the water, the amount of minerals in the water, the temperature, and the length of time the water stays in the pipes. Drinking water is responsible for 14-20 % of Pb poisoning in the United States[33].
- **Lead Paint:** Another potential source of Pb is lead paint. Lead carbonate [$PbCO_3$/$Pb(OH)_2$] is added to the paint to increase durability, expedite drying, and protect the surface from corrosion. Because lead paint dust collects from peeling, flaking, and cracking, children are the most affected.
- **Lead at Work:** Adults who work in lead-containing industries such as battery manufacturing, electronic components, pipe fitting, glass production, and smelting activities are lead sources and should take steps to avoid contamination[34].
- **Contaminated Soil:** Contaminated soil can come from leaded gasoline and industrial operations such as smelters.
- **Lead-based items:** Engine oil, jewelry, lunch boxes, and dishwashers are all significant sources of Pb.