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Possibilities for Hardness Enhancement of Lead-Based Alloys: A Review

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Abstract: Antimony plays a crucial role in lead-based alloys, primarily enhancing their mechanical properties and resistance to corrosion. It is commonly used as a hardening agent in lead alloys, improving their durability and performance in various industrial applications. However, the use of antimony has become increasingly problematic due to its limited availability and the challenges associated with its procurement. This article addresses the need to replace antimony with alternative alloying elements, exploring potential substitutes that can provide similar or enhanced properties. The paper investigates various alloying elements, such as tin, copper, and others, evaluating their effectiveness in replacing antimony in lead-based alloys. It also examines the impact of these substitutions on the physical, mechanical, and chemical properties of the alloys. The aim is to offer a comprehensive understanding of how these alternative elements can optimize the performance of lead alloys, ensuring sustainability and reliability in their applications.

1. Introduction

Be advised that papers in a technically unsuitable form will be returned for retyping. After returned the manuscript must be appropriately modified. Antimony (Sb) is one of the most used alloying elements in lead (Pb)-based alloys [1], which are widely applied in various industrial sectors [2], such as ammunition manufacturing, battery production, printing type production, and bearing alloy preparation [3-4]. The addition of antimony to lead significantly enhances the alloy's mechanical properties, particularly hardness, strength, and wear resistance [1]. Lead-antimony alloys have been widely used in the production of cable sheathing and battery grids. Antimonial lead alloys containing 1–5 wt.% antimony have been successfully produced through both continuous and gravity casting methods [1]. This is primarily due to the finer grain distribution resulting from the antimony, which improves the stability and durability of the crystal structure.

The presence of antimony also improves the castability and machinability of the alloy, which is especially important in applications that require precision moulding or casting. In ammunition production, for example, bullets made from lead-antimony alloys have a significant advantage in terms of hardness and shape retention. In battery manufacturing, antimony increases the strength of the grid structure, which is critical for long lifespan and mechanical stability.

In the literature review, particular attention is given to the investigation of the effects of antimony as an alloying element on the microstructure and mechanical properties of lead [5-6]. The research aims to understand the extent of grain refinement caused by antimony, the behaviour of dislocations, and the resulting increases in the alloy's strength and hardness. However, the goal of the research is not only to examine these effects in detail but also to explore alternative alloying elements that provide similar beneficial properties to antimony. Efforts to replace antimony could be especially important due to environmental, health, or economic considerations. Finding new alloying elements may contribute to the development of more sustainable and safer materials, while maintaining or even improving the desired mechanical properties.

2. Pb-Sb phase diagram

In an antimony-lead alloy, the phase diagram (Figure 1.) plays a crucial role in understanding the material's casting characteristics, particularly in terms of the casting temperature and solidification process. The phase diagram reveals the eutectic point, which is important for the casting process. The lead-antimony alloy is a low melting point binary eutectic alloy system [7]. Typically, the eutectic composition of lead-antimony alloys occurs at eutectic temperature of approximately 240 ℃.

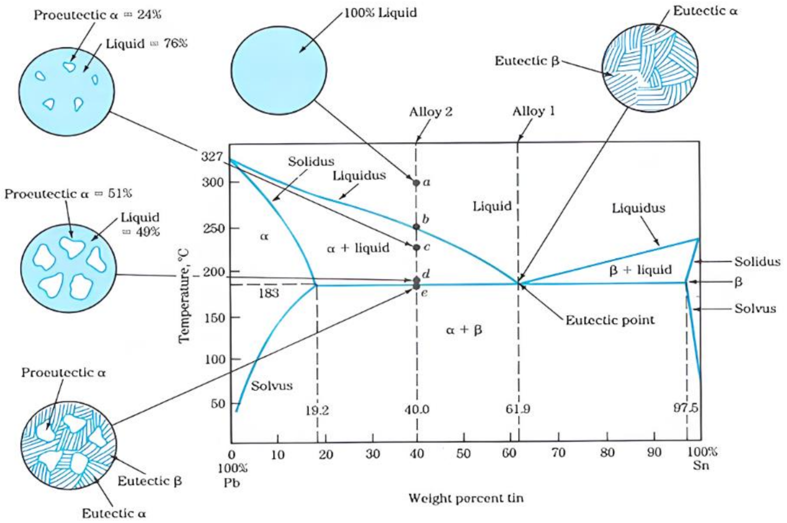

Figure 1. Phase diagram of Pb-Sb alloy [7]

According to the Pb-Sb phase diagram, in a lead alloy with 0.44% antimony content, antimony does not dissolve below 100 ℃. It remains undissolved both below and above this temperature. At this point, grain growth begins. The Pb-Sb phase diagram shows that antimony forms an eutectic phase with lead. When a liquid with an eutectic composition solidifies, an eutectic microstructure forms, consisting of layers of α and β phases. Antimony-rich grains form when the antimony concentration in the Pb-Sb alloy exceeds the solubility limit, which is only 0.44 wt% at 100 ℃. This results from the precipitation of antimony from the alloy in this state, such as in other alloy, which has a 1.25 wt% antimony content at 382 ℃. Therefore, most of the antimony dissolves in lead, and antimony-rich grains precipitate from the Pb-Sb solid solution.

From a casting perspective, the optimal casting temperature is usually just above the eutectic point, which ensures that the alloy is fully liquid and can flow easily into moulds. If the temperature is too high, the alloy can suffer from excessive oxidation, which can impair the quality of the casting. Conversely, if the temperature is too low, incomplete filling of moulds or the formation of undesirable microstructures (such as coarse grains or phase separation) can occur.

The presence of antimony in the alloy increases its melting point compared to pure lead, thus requiring a slightly higher casting temperature. However, because the eutectic composition results in a lower melting point compared to alloys with higher antimony content, careful control of the casting temperature is necessary to avoid defects.

In addition, the solidification process of antimony-lead alloys can influence the final microstructure, which impacts the mechanical properties of the casted parts. The phase diagram also indicates that the solidification process involves the formation of a solid solution and a eutectic structure, which can affect the material's overall hardness, strength, and corrosion resistance.

Therefore, understanding the phase diagram is essential for optimizing the casting process, controlling temperature, and ensuring the desired quality and properties of the final product.

3. The role of antimony in lead alloys

Antimony is an important alloying element in lead alloys and can be used to improve various properties. One of its most important roles is increasing the hardness and strength of the alloy [8]. Lead, in its pure form, is quite soft and weak; therefore, when higher strength or wear resistance is required, these properties are often achieved by adding antimony [9]. The properties of the alloy are determined by its chemical composition. The addition of antimony to lead primarily improves the mechanical properties, while high antimony content has a negative impact on the electrochemical properties [10]. Figure 2. illustrates how the hardness of lead alloys changes as a function of antimony content by weight percentage. Antimony is one of the most widely used alloying elements to increase the hardness of lead. Even at low concentrations (0.5–1%), it significantly enhances hardness, which is highly beneficial from an industrial perspective.

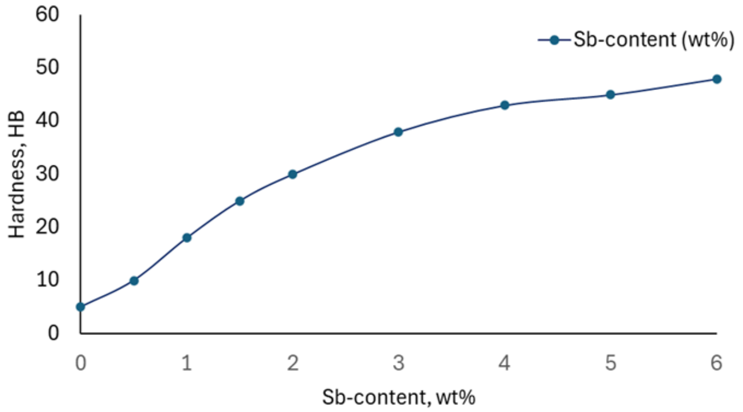

Figure 2. Effect of Sb-content on the hardness of lead alloy

Pure lead has a low Brinell hardness, making it unsuitable for many applications. However, by adding antimony, the hardness increases rapidly: between 1–2% antimony content, values in the range of 20–30 HB can be achieved. With 4–5% antimony, the hardness often exceeds 40 HB, making the alloy suitable for applications such as bullet casting, battery terminals, or other components where wear resistance and mechanical stability are important. The shape of the curve indicates that the effect of antimony is non-linear: the initial increase in hardness is steep, but beyond 4–5%, the effect begins to saturate. Therefore, alloys containing more than 6% antimony are rarely used in practice, as they provide little additional mechanical benefit while increasing material costs and potentially making the alloy more brittle.

It results in a finer grain structure, which improves castability and machinability. This is especially beneficial in applications that require precision casting or moulding. One disadvantage of using antimony is that if present in too high a quantity, it can make the alloy brittle. Therefore, the alloying ratio must be carefully determined based on the specific requirements of the application.

3.1. Microstructural effects

Ehsaan-Reza et al. [5] investigated the effect of antimony on the mechanical properties and microstructure in their research. In their study, pure lead and an alloy containing 1.25% Sb were compared. Figure 3. shows the effect of Sb on the microstructure of lead, in case of pure lead and 1,25 wt% Sb-content.

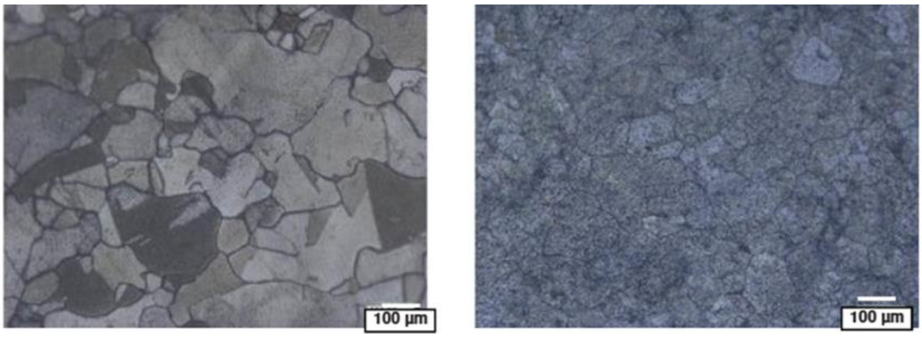

Figure 3. Effect of Sb-content on microstructure of lead, magnification ×100 (left: pure lead, right: 1,25 wt% Sb) [5]

Pure lead has a higher percentage of elongation at break and lower tensile strength than the antimony-alloyed lead. The change in mechanical properties is since lead has an FCC lattice structure, while antimony has a BCC lattice structure. In the BCC lattice, the mobility of dislocations is significantly worse compared to the FCC lattice, meaning dislocations move much faster in the FCC lattice, making it more ductile. Examining the fracture surface, both pure lead and antimony-alloyed lead fracture in a ductile manner; however, in the case of pure lead, necking is observed alongside the plastic deformation.

Further examination of the microstructure reveals that in the antimony-alloyed alloy, the grain size is smaller, and dark spots (presumably antimony) are present in the microstructure, which may indicate precipitation. Additional alloying elements generally result in finer and more homogeneous precipitation distribution. Due to the finer grains, precipitation occurs in more places. As a result, the Pb1.25%Sb alloy shows higher tensile strength than pure lead. The addition of antimony to lead results in grain refinement. One possible reason for grain refinement is the increase in melting temperature, as pure lead has a melting point of about 327 ℃, whereas the Pb-Sb alloy has a melting point of 380 ℃. As a result, grains in the structure crystallize into finer grains. Generally, smaller/finer grains have a larger grain boundary area, which impedes dislocation movement, and reducing the grain size increases the available nucleation sites. Therefore, reducing grain size typically increases toughness, as dislocations interact with grain boundaries. Larger grains contain more dislocations within the grain itself. However, in smaller grains, there is a much higher chance that a dislocation will be stopped at the grain boundary [11]. Pola's research [11] indicated that Pb-Sb alloys with 1.5±3.5 wt% Sb become brittle and are prone to cracking due to their dendritic structure [12]. The cooling rate significantly affects the crystallization mode. If the alloy cools slowly during solidification, solid phases such as α-Pb crystals tend to grow in long, branched dendritic structures. However, the small amount of antimony can limit the crystallization process, which also promotes the growth of dendrites due to the differences in solubility and growth dynamics between phases. Grain refinement occurs at the eutectic transformation temperature.

3.2. Castability

In general, the addition of antimony to lead reduces its castability, which can be explained by the increase in solidification temperature and the increase in viscosity. The addition of antimony raises the solidification temperature of the lead alloy. Due to the higher solidification temperature, molten lead cools more slowly and is more likely to solidify before completely filling the mould. This can lead to shrinkage or incomplete mould filling, resulting in cracks, voids, or poor surface quality in the casting. Alloying with antimony also affects crystallization, and thus brittleness. Rapid crystallization leads to uneven solidification, making proper mould filling more difficult. This can result in internal stresses or surface defects.

Antimony also significantly affects the viscosity of lead, as antimony forms a solid solution with lead, influencing the interaction between the metal atoms. Due to antimony's higher atomic mass and other chemical properties, its incorporation into the lead crystal structure tightens the interactions between atoms. This stronger bonding increases the viscosity of the alloy, as the interactions between molecules and atoms become stronger. As the viscosity increases, the flow rate decreases.

Another explanation is that antimony forms harder intermetallic compounds with lead, resulting in more rigid, less mobile structures. This chemically stable but stiffer structure reduces the mobility of the molten alloy, thereby increasing its viscosity.

4. Possible alloying elements

When selecting an alloying element to replace antimony, four factors should be considered to improve the mechanical properties 1) decrease in melting point; 2; decrease in viscosity; 3) improvement in solidification in behaviour; 4) Improvement in mechanical properties

The relevant literature suggests arsenic, copper, tin, and bismuth as alternatives to antimony for increasing the hardness of lead alloys. The following table examines the effect on hardness and castability of lead alloys, compared to antimony:

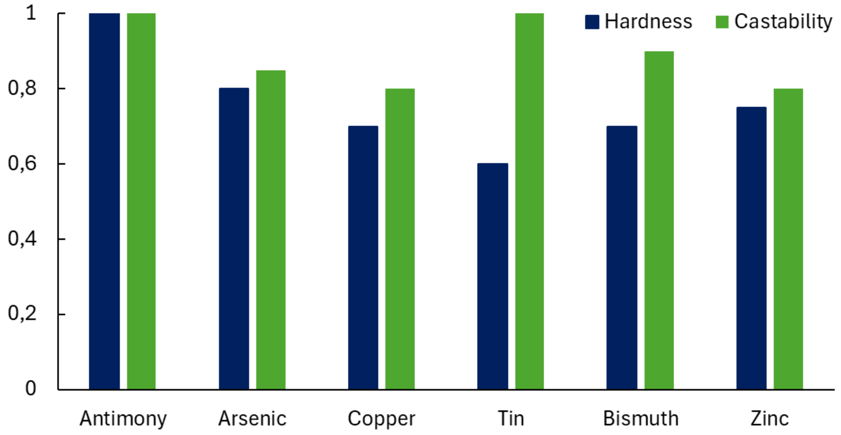

Figure 4. Effect of alloying elements on the hardness and castability of lead

Figure 4 shows that antimony is considered the most effective alloying element for increasing hardness (reference value: 1). Other alloying elements are less effective in comparison for increasing hardness. Table 1 shows the effect of alloying content on the Brinell hardness of lead.

All alloying elements improve castability, although to varying degrees. The best castability is provided by tin. The castability is improved by the following actions of the individual alloying elements:

- Arsenic: reduces the melting point and results in a finer crystal structure.

- Copper: reduces the viscosity of the molten metal and improves cast filling.
- Tin: significantly improves the melting and solidification behaviour.
- Bismuth: aids in uniform casting.
- Zinc: increases hardness by modifying the lead crystal structure but reduces castability.

Table 1: Effect of alloying elements on the hardness of Pb

Alloying element	Concentration	HB	Ref.
Pb	5 HB		-
Sb	1% → 6%	9 → 30 HB	[28]
Sn	0.5% → 5%	6 → 12 HB	[28]
As	0.1% → 0.5%	6 → 10 HB	[15]
Cu	0.5% → 2%	8 → 10 HB	[14]
Zn	0.5% → 2%	6 → 9 HB	[28]
Bi	0.1%→2%	4.5→ 18 HB	[15]

4.1. Arsenic

Arsenic, when added to lead alloys, significantly increases the alloy's resistance to bending and creep. The maximum hardness of a lead-arsenic alloy can be achieved by heat treatment. However, during storage at room temperature, arsenic may precipitate, which can lead to softening of the alloy [16].

The eutectic point of the arsenic–lead system is at 7.4% arsenic and a temperature of 288 °C. The solubility of arsenic in lead is extremely low: at 290 °C it is 0.14 at%, while at room temperature it is less than 0.03 at%. [17].

Arsenic influences the mechanical and physical properties of lead alloys, as well as their corrosion resistance. Increasing the amount of arsenic can increase the hardness of lead alloys, especially when antimony is also added. Even small amounts (0.1-0.5%) can significantly improve the hardness and mechanical strength of the alloy without decreasing its formability [18].

Certain sources report [19] that during casting, arsenic in lead alloys can reduce the amount of shrinkage and shrinkage cracks in the final product, which can be achieved with around 0.1-0.15% arsenic content. However, with an arsenic content of 0.2-0.6%, the corrosion resistance of the alloy can be improved. The increased arsenic concentration increases the hardness of the alloy but can also lead to an increase in its brittleness. Increasing the arsenic content may result in grain refinement by influencing the degree and rate of crystallization in the lead crystal structure. Arsenic can inhibit crystal growth, which results in a finer grain structure and potentially improved mechanical properties [20].

Figure 5. Effect of As-content on the microstructure of lead, magnification: ×400 (from left to right: 4 at%, 5 at% and 11 at% As-content) [17]

When arsenic is alloyed with other metals, segregation phenomena may occur, leading to microstructural inhomogeneities within the alloy. Arsenic can aggregate at the boundaries of the crystalline matrix during cooling and solidification, which may cause microstructural distortions. Figure 5 shows the Effect of As-content on the microstructure of lead.

Arsenic also affects the alloy’s corrosion resistance [21-22]. It can increase the corrosion resistance of lead alloys, especially in acidic environments [23]. This could be particularly advantageous in applications such as battery manufacturing.

Arsenic’s presence may also impact the solidification process, improving castability and reducing internal defects. It can also affect the crystallization of lead, reducing the tendency for dendritic structures to form, which results in a more uniform and stable alloy.

While arsenic has several favourable effects on the properties of lead alloys, its use is not without concerns, especially in the manufacturing of projectiles. Arsenic is highly toxic, particularly to internal organs. Long-term exposure to arsenic can increase the risk of cancer. The International Agency for Research on Cancer (IARC) [24] classifies arsenic as a human carcinogen (Group 1). The US National Toxicology Program (NTP) and the EPA [25] also consider arsenic highly hazardous, particularly with long-term exposure.

If arsenic is present in projectiles and they explode or become damaged during use, arsenic can easily contaminate the environment and potentially endanger human health. The use of arsenic in projectiles is subject to strict environmental and safety regulations. The use of such materials in projectiles is not only dangerous but may also pose serious legal and regulatory challenges.

4.2. Copper

Lead (Pb) and copper (Cu) alloys are found in various industrial applications, especially where specific mechanical and physical properties are required [26]. Adding copper to lead induces significant changes in both the microstructure and mechanical properties. Understanding these changes is crucial for designing and applying optimal alloys.

Copper is often used in lead alloys, particularly in applications where electrical conductivity, corrosion resistance, and/or heat resistance are required. Compared to antimony, copper provides similar hardness. [27].

The solubility of copper in lead is limited [28-29], which results in copper existing as a separate phase in the lead matrix, such as in the form of intermetallic compounds. This phase separation influences the alloy's microstructure and affects its mechanical properties. The microstructure of lead-copper alloys is highly dependent on the alloying method and heat treatment procedures. The limited solubility of copper in lead results in the formation of distinct phases within the lead matrix [30]. These phases can create a fine-grained structure, which influences the alloy's mechanical properties. For example, the fine-grained structure can increase the material's strength and hardness.

The copper content, as mentioned above, can fundamentally increase the hardness of lead. Determining the optimal copper content is important because excessive copper content can lead to the brittleness of the alloy. The presence of copper increases the tensile strength and yield strength of lead, making the alloy more resistant to mechanical stresses.

4.3. Tin

The solidification ranges and solid solubility limits of lead-tin alloys can be obtained from the equilibrium phase diagram. Tin improves the mechanical properties in most lead-based alloys [31-32]. Lead-based alloys tend to deform easily and have relatively low strength. By adding tin, both strength and hardness can be increased, improving the applicability of the alloys for various mechanical stresses [33]. Tin has a positive effect on the crystal structures, as it can stabilize the alloy, reducing the risk of cracking and breaking. Additionally, tin can improve fatigue properties, which is especially important in applications where products are subjected to continuous mechanical stress.

In the case of lead-tin alloys, a correlation is observed between hardness and tensile strength. However, irregularities are seen at 16% tin content, which is the point of limited solubility. Up to 30% tin content, there is a gradual increase in mechanical properties, continuing up to 45-50%, after which they start to decrease. The first effect of adding tin to lead is a decrease in the percentage of elongation up to 15% tin content. As the tin content exceeds this concentration, elongation increases and can exceed 100%, a value that remains constant up to a 50% tin concentration [34].

The addition of tin to lead causes various microstructural changes, primarily in terms of crystal structure and grain growth. Tin dissolves in lead and can stabilize the solid solution, which helps achieve better mechanical properties.

The crystal structures of tin and lead are similar, which allows tin to dissolve in lead. Tin atoms incorporate into the lead crystal lattice, forming a solid solution that increases the alloy's strength and hardness. Additionally, tin enhances the stability of the alloys, reducing the risk of cracking and breaking.

The presence of tin reduces the grain size of lead, resulting in a finer structure. Finer grains contribute to the improvement of mechanical properties, such as increased strength and fatigue resistance. The finer grains increase the number of grain boundaries, which results in stronger bonds between the metal lattices [34].

Adetunji and colleagues [35] investigated the mechanical and microstructural properties of lead alloys with different tin contents. The conducted studies revealed that higher lead content decreases the hardness of the alloy. The fracture surfaces of the samples exhibited a brittle-ductile transition.

Alloying with tin can also induce directional crystallization, which improves the strength and reliability of the products. In the microstructure, tin can help form needle-like or lamellar crystals, which increase the material’s strength and hardness, as well as reduce the propagation of cracks.

4.4. Bismuth

Bismuth, in terms of its properties, is like lead and is often found in lead ores. The bismuth-lead alloy forms an eutectic phase diagram [37]. According to the literature, in the lead-bismuth alloy, the maximum hardness is achieved at the eutectic temperature with a bismuth content of 50%. Tensile tests show that as the bismuth content increases up to 25 wt%, the tensile strength continuously increases. This can be explained by the fact that after reaching solid solubility, the alloy's structure becomes inhomogeneous. Between 25% and 35%, a decrease in tensile strength is observed, likely due to the formation of precipitates, and above 35% bismuth content, the tensile strength increases again. In parallel, the percentage elongation gradually decreases as the bismuth content increases, and irregularities are observed again at the boundary of solid solubility.

Regarding hardness, it can also be stated that with increasing bismuth content, hardness increases up to 20% bismuth content, remains constant between 20% and 45%, and then continues to increase beyond 45%. However, the hardness-enhancing effect is less significant when compared to antimony added to the alloy in similar proportions [20].

It should be noted that at higher concentrations, bismuth can cause brittleness in the alloy [38]. The advantage of bismuth is that during melting and solidification, the alloy can undergo up to a 3.5% expansion, which can be particularly beneficial in applications where the precision of the casting is a critical criterion [39].

Bismuth can be a good alternative to antimony, as it shares similar chemical and mechanical properties and can help increase hardness. However, as mentioned above, alloying with bismuth can make the casting more brittle, whereas antimony provides better mechanical strength. The advantage of bismuth, however, is that it is less toxic than antimony, making it a safer alternative in applications where toxicity could be a concern.

While bismuth offers the possibility of partial or even complete replacement of antimony, in ammunition manufacturing, it must be considered that bismuth does not provide the same mechanical and strength properties that antimony does. Therefore, bismuth is not always an ideal or fully suitable substitute for antimony in ammunition. The choice of material depends on the specific alloys and the desired properties combination.

4.5. Zinc

Lead and zinc atoms have different sizes and crystallize according to different crystal structures. Lead crystallizes in a face-centered cubic (FCC) lattice, while zinc forms a hexagonal close-packed (HCP) structure. During alloying, zinc atoms integrate into the lead crystal lattice; however, since zinc atoms (135 pm) and lead atoms (180 pm) [40] have different atomic sizes, the lattice structure is distorted, and internal stresses may arise within the structure [41]. This structural distortion can reduce the material's flexibility and castability. The mismatch between the lead and zinc atoms can also limit the movement of lattice defects and dislocations, which in turn affects the solidification process of the casting.

The castability of lead refers to the behaviour of the material during the transition from the liquid phase to the solid phase and how the casting behaves during the casting process. Key factors affecting castability include the viscosity of the liquid phase, the melting point, and the bonding forces between the solid-state lattices. The addition of zinc to lead raises the melting point, making the mixture more difficult to cast, and shifts the solidification process. Zinc may contribute to an increase in the hardness of the solid phase, but as mentioned above, it can hinder dislocation movement. Antimony provides hardness, strength, and wear resistance in lead alloys, while zinc, on the other hand, results in lower strength and can make the alloy more brittle, particularly in cold environments. While zinc can help lower the melting point of alloys, it does not provide the same level of hardness and strength as antimony does. [42]. It should also be noted that zinc can worsen the castability compared to antimony. During casting, the lead alloyed with zinc often exhibits foaming, which can be caused by several factors:

a) Gases entering the melt: The melting point of zinc is higher than that of lead, which increases the casting temperature. During the high-temperature casting process, zinc and lead may react with the oxygen in the air, potentially generating oxygen gas. When the molten metal suddenly meets the air, oxidation reactions may occur, leading to gas formation. If a significant amount of oxygen enters the melt in the form of bubbles, these bubbles can cause foaming in the casting.

b) Zinc tends to absorb hydrogen in its molten state, especially if water or moisture enters the melt, which can result in the formation of hydrogen gas. The incorporation of hydrogen into the molten metal and its subsequent solidification can lead to the formation of bubbles and pores in the casting, which can be perceived as foaming. Gases like hydrogen can be released during the solidification of the casting, and the accumulated gases can cause the alloy to foam.

c) Improper casting temperature, rapid solidification: If the casting temperature is too high or the metal solidifies too quickly, the zinc-lead alloy may tend to release gases during cooling and solidification. In the case of rapid solidification, not all gases can escape from the molten metal, and these gases exert internal pressure, leading to the formation of bubbles or pores, which can result in foaming.

d) Oxidation products and surface reactions: The oxidation of zinc-lead alloys may increase during the casting process since zinc easily oxidizes at high temperatures. During oxidation reactions, oxygen and gases such as carbon dioxide may enter the casting. The resulting oxides and gases can form bubbles inside the casting, which also contributes to foaming.

e) Improper casting technology and contaminants: Contaminants present during the casting process (e.g., water, moisture, oils, or other impurities) can react with the molten metal, causing gas formation. These contaminants can enter the casting and produce gases that cause bubbling and foaming.

To avoid foaming in zinc-lead alloys, the following methods are recommended:

- Optimizing the casting temperature – higher casting temperatures promote gas formation.
- Vacuum casting.
- Deoxidation: Removing gases from the alloy using deoxidizing agents.
- Anti-foaming agents: Anti-foam agents, as surfactants, reduce the interfacial tension between the metal and oxygen, making it easier for gases to escape from the molten metal. This reduces the extent of foaming, and the castings become cleaner and stronger.

5. Conclusions

In the production of lead-based ammunition, the role of antimony is crucial, as the addition of antimony improves the strength and hardness of lead. However, the use of antimony can lead to environmental and health issues, as antimony has toxic effects, particularly in industrial work environments. As a result, industries are searching for alternatives that can replace antimony without compromising performance.

1) Arsenic has a similar effect to antimony as it increases the hardness and strength of lead. Arsenic-lead alloys have good corrosion resistance and can improve the performance of ammunition. However, arsenic is highly toxic, and due to its effects on human health, its use is restricted, particularly because of occupational health and environmental regulations. This drawback significantly reduces the applicability of arsenic as an alternative.
2) Copper improves the mechanical properties of lead alloys, particularly strength and corrosion resistance. The use of copper reduces the wear of ammunition and provides a significant advantage in long-term storage and use. Copper is non-toxic, making it an environmentally friendly alternative. The downside of copper is that it may increase the melting point of the alloy, and in larger quantities, it can have a brittle effect.
3) Tin is a promising alternative because it can improve the strength, hardness, and heat resistance of lead while being non-toxic and environmentally friendly. Tin not only improves the mechanical properties of ammunition but also contributes to reducing oxidation processes.
4) Zinc also improves the strength and hardness of ammunition while reducing oxidation. It is a cost-effective and environmentally friendly alternative that can be widely used in various metal alloys. The application of zinc also improves the heat resistance of metals. However, zinc can cause brittleness in alloys, and when used in excessive amounts, it can make the alloys more brittle. Zinc-lead alloys also have a higher melting point, which can cause issues in manufacturing processes.
5) Bismuth is one of the best alternatives to replace antimony, as it has similar mechanical properties but is much less toxic. Alloys made with bismuth have good strength, hardness, and higher corrosion resistance. Additionally, bismuth does not pose an environmental risk and is safer to handle. Its drawback is that it is a less cost-effective solution for replacing antimony.

Alternatives to antimony, such as arsenic, copper, tin, zinc, and bismuth, offer various advantages and disadvantages. While bismuth is one of the most promising and safest alternatives, zinc and tin are cheaper but offer more limited performance. Arsenic, although it has similar benefits, is highly toxic, which limits its application. Literature research and phase diagram analysis enable the selection of the best alternative to produce lead-based ammunition, considering environmental, economic, and performance aspects.

Choosing the appropriate alternative for replacing antimony requires not only theoretical research but also experimental work to ensure the actual applicability of the alternative materials. This process must assess the properties of the currently manufactured products and determine whether they meet the desired requirements, such as strength, hardness, and corrosion resistance.

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