Copper-based alloys: Influence of alloying content on their thermo-mechanical properties and applications

Susana Montecinos[a, b, c*], Sebastián Tognana[a, b, d**], Carlos Frosinini[a, b, d]

[a] *Universidad Nacional del Centro de la Provincia de Buenos Aires (UNCPBA), Facultad de Cs. Exactas, IFIMAT, Tandil, Buenos Aires 7000, Argentina*
[b] *CIFICEN, UNCPBA-CICPBA-CONICET, Tandil, Buenos Aires 7000, Argentina*
[c] *CONICET, Buenos Aires 1425, Argentina*
[d] *Comisión de Investigaciones Científicas de la Provincia de Buenos Aires, Buenos Aires 1900, Argentina*

Correspondence to: Universidad Nacional del Centro de la Provincia de Buenos Aires (UNCPBA), Facultad de Cs. Exactas, IFIMAT, CIFICEN, Argentina.
E-mail addresses: dmonteci@ifimat.exa.unicen.edu.ar (*S. Montecinos), stognana@ifimat.exa.unicen.edu.ar (**S. Tognana)

Abstract

Copper is a metal widely used in engineering and in various industrial applications, due to its excellent properties of high electrical and thermal conductivity, good corrosion resistance, good mechanical properties, and ease of processing. In addition to its good mechanical and physical properties, copper has antimicrobial properties against bacteria, viruses and fungi, and promising biological performance. For certain specific applications it is necessary to add alloying elements that give the material particular properties. The most common and commercially available copper-based alloy families are brasses, bronzes, silicon bronzes, aluminum bronzes, and beryllium bronzes. Age-hardenable Cu-2Be alloy can exhibit high strength and hardness after the formation of γ′ metastable nanoprecipitates by aging treatments. After 45 minutes at 400°C, the material can reach a hardness of 354 HV and an elastic modulus of almost 120 GPa. Aluminum bronze Cu-9Al-4Fe is an alloy that contains α, β′ and intermetallic κ phases. Aging treatments at 400°C produce a slight increase in hardness and elastic modulus due to changes in the fraction of phases present. The selection of the required material and the heat treatments to be performed must depend largely on the specific application and the demands placed on the material. On the other hand, for the study of these materials, different aspects must be considered, such as the size of the phases present and the detection capacity of the constituent elements. In particular, the study of aged Cu-2Be alloys requires careful studies, due to the nanometric size of the precipitates and the low atomic number of Be.

Keywords: Cu-based alloys, mechanical properties, microstructure, age-hardening.

1.- Introduction

Copper is a metal widely used in engineering and in various industrial applications, due to its excellent properties: high electrical and thermal conductivity, good corrosion resistance, good mechanical properties and ease of processing [Smith, 1998]. Most copper is extracted from ores containing copper and iron sulfides. These are smelted and both the sulfides and other impurities are removed as slag, resulting in fire-refined copper with 98% Cu. However, copper generally undergoes an electrolytic refining process to obtain a purity of at least 99.95% (electrolytic copper). **Ordinary commercial electrolytic copper** (ETP (Electrolytic Tough Pitch) copper) has a nominal oxygen content of 0.04%, which forms interdendritic cuprous oxide, which constitutes an insignificant impurity in the material obtained. According to the Unified Numbering System (UNS), ETP copper is assigned as C11000 and has a minimum conductivity of 100% IACS. It is mostly used for electrical and electronic conductors, buss bars in electrical power installations, channels, roofing, car radiators, nails, rivets and machinery elements, among others. However, when copper is subjected to high temperatures in the presence of hydrogen, steam is produced that diffuses into its interior, causing the material to become brittle [Smith, 1998]. This is why, by electrolytic copper refining process, most of the oxygen and other contaminants it contains can be removed, resulting in a material with between 99.95 and 99.99% copper and a maximum of 0.0005% oxygen, which is called **oxygen-free high thermal conductivity** (OFHC) C10100 copper. The copper thus obtained has better properties, such as thermal and electrical conductivity (101% IACS), ductility, impact resistance, mechanical resistance and durability, greater and better resistance to corrosion and better ability to transfer low-frequency sounds. Due to these properties it is used for electrical and electronic conductors, glass to metal seals, vacuum tube and solid state devices, super conductor matrixes, wave guides and cavity resonators, among others [NSRW, 2025]. In addition, it is used for specific applications for high-precision components in the electronics industry, in communication and avionics systems in the aerospace industry, in electric and hybrid vehicles in the automotive industry, in telecommunications, energy and power, and in medical applications [MicroPlanet, 2024]. On the other hand, there is the **oxygen-free copper** (OF) or C102000, which has a minimum conductivity of 100% IACS, an oxygen content of 0.001% and a purity of 99.95%.

In addition to the composition, the microstructural characteristics of metals have a great influence on their mechanical and physical properties. Using severe surface plastic deformation (SSDP) methods it is possible to obtain gradient structured (GS) materials with excellent balance between strength and ductility. Studies on GS pure copper prepared by surface mechanical attrition treatment have found that, compared to a homogeneous coarse grain copper material, the yield strength of the material can be increased by almost 5 times, with a uniform elongation of 19% [Li et al., 2025]. This improvement in the mechanical properties of SMAT samples is due to the grain size gradient and the geometrically necessary dislocation gradient.

Copper pieces for applications in power and electrification products, electronic, automotive and aviation industry and heat management systems, among others, are traditionally produced by methods based on subtractive manufacturing or by sand casting. Also, production of components by machining implies high material and labor consumption, besides of long production time and high cost. However, in the last years, the production of geometrically complex copper components by additive manufacturing has been investigated, especially for electrical conduction, electromagnetic applications and heat management applications [Jadhav et al., 2021; Liu et al., 2024; Malec et al., 2024; Qu et al., 2021]. Pure copper presents certain limitations for the manufacture of components using additive manufacturing, due to its high thermal conductivity, which causes high temperature gradients and delamination of the deposited layers, the high plasticity of copper, which makes difficult to recover the copper particles after manufacturing, and the facility of copper to the surface oxidation. Taking these limitations into account, the most promising technologies that can compete with conventional technologies are binder jetting and direct metal laser sintering [Malec et al., 2024]. In order to obtain copper parts through additive manufacturing with high electrical and thermal conductivity, good mechanical properties and smooth surface finishing, research has been carried out by modifying the manufacturing parameters, such as power and wavelength laser, among others [Jadhav et al., 2021; Qu et al., 2021]. Other researchers designed a strategy to solve those problems, dispersing a small quantity of lanthanum hexaboride nanoparticles in pure copper through laser powder bed fusion [Liu et al., 2024]. This strategy improves the processability, strength and thermal stability, and maintains the high conductivity of the pieces. On the other hand, cold spray technology is an emerging solid-state connection method that has been mainly used for a preparation of metal-based specific mechanical structures or parts with fully dense deposits. In cold spray technique, powders are accelerated by a gas and impacted onto a substrate at a high velocity. Huang et al. studied the microstructural evolution, phase constitution and relationship between the microstructure and tensile behavior of pure copper parts fabricated by cold spraying technology [Huang et al., 2020]. Only equiaxed grains were detected, without other substructure, 73% IACS and excellent mechanical properties compared to pieces fabricated by selective laser melting and other conventional techniques. Li et al. studied this technique using a mixed feedstock of two raw copper powders: a hard and dense gas-atomized and a soft and porous electrolytic powder, so that the deformation is concentrated on the soft side, the inter-particle space is filled by the deformed soft particles and a fully dense microstructure is obtained [Li et al., 2018]. In this way, the coating prepared shows an excellent corrosion resistance, comparable with that of the bulk copper. Other researchers have studied the influence of a preliminary heat treatment of 390 K for 12 h at 10^{-3} MPa on copper powder used as feedstock on the deposition process and coating properties, and found that this process leads to an increase in the deposition efficiency of coating [Klinkov et al., 2020].

In addition to its good mechanical and physical properties, copper has antimicrobial properties against bacteria, viruses and fungi. The main mechanism of bactericidal activity is the generation of reactive oxygen species, which results in membrane damage, while the main mechanism against viruses is ion release leading to RNA degradation and disruption of the membrane of enveloped viruses [Salah et al., 2021]. Copper also shows promising biological performance in cell migration, cell adhesion, osteogenesis, chondrogenesis and angiogenesis [Wang et al., 2021]. According to several studies, it can endow functional properties for bone and cartilage repair by direct cell behaviors and modify the physicochemical properties of biomaterials. In vivo animal studies have shown that copper is beneficial for the repair of bone, cartilage and blood vessels [Wang et al., 2021].

2.- Copper alloy families

Despite all the good properties of copper as a pure material, for certain specific applications it is necessary to add alloying elements that give the material particular properties, depending on the required performance. As mentioned above, copper is one of the materials with the highest electrical and thermal conductivity, making it ideal for its use in electronic wiring and connections applications. For applications where greater strength and durability is required, maintaining its cold-forming properties, it is usually added tin, nickel and other materials [Sequoia, 2025]. The most common and commercially available copper-based alloy families are shown in Figure 1.

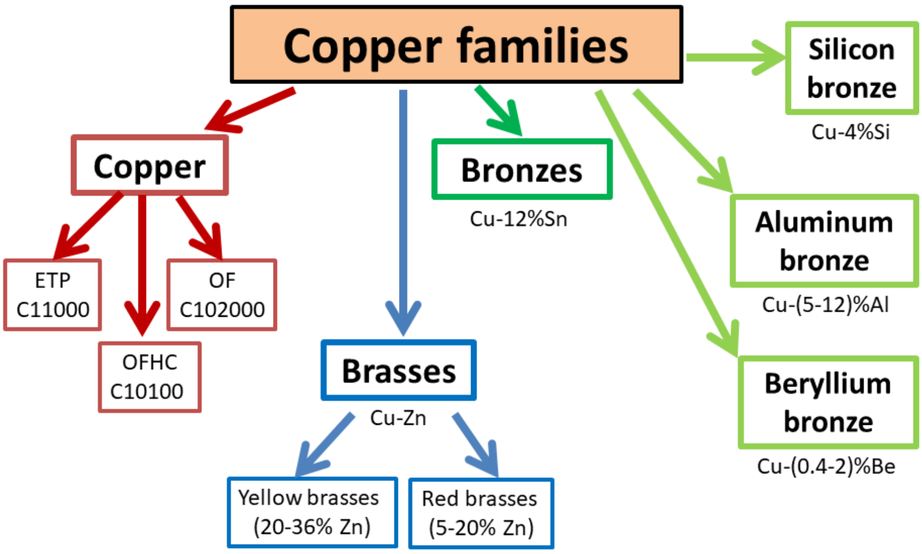

Figure 1. Diagram showing commonly used copper families.

The main characteristics of each family are [Sequoia, 2025; Singh, 2020]:

- **Brasses** are copper-based alloys, which contain mainly zinc and other metals like lead, tin, iron, aluminum, silicon, and manganese. The addition of zinc enhances the strength and ductility of the alloy, and as the zinc content increases, the material becomes more pliable. Alpha brass contains up to 36% Zn and can be found as yellow brasses (contain between 20 and 36% Zn), with high ductility and strength, and red brasses (contain between 5 to 20% Zn), which have better corrosion resistance than yellow brasses. These alloys exhibit susceptibility to stress-cracking, malleability and formability, high melting point and non-ferromagnetic properties, which makes it much easier to process for recycling. Yellow brass is often used as decorative and architectural element. Due to its workability and machinability, it is also used in the manufacture of plumbing, electronics, electrical components, automotive parts and musical instruments.

- **Bronze** contains typically 88% Cu and 12% Sn, with trace amounts of other metals, such as aluminum, manganese, phosphorous, and silicon. However, the name bronze is also used for copper alloyed with silicon, aluminum, and beryllium, which are called: silicon bronze, aluminum bronze and beryllium bronze, respectively. Bronze exhibits attractive finish, excellent thermal conductivity, strength, resistance to saltwater corrosion and high ductility, and its main applications include bushings and bearings, electrical connectors and springs, marine applications and petrochemical tools.

Silicon bronze alloys contain 96% Cu and the remainder may be just silicon, but more often some manganese, tin, iron, or zinc is added. They are used for architectural applications and for the chemical industry due to their exceptional resistance to corrosion in many liquids.

Aluminum bronze contains between 5 to 12% Al, along with various combinations of other metals. Those containing up to 7.5% Al are extremely ductile, and are especially useful for deep stamping, spinning, and severe cold-working. Those containing between 8 to 11% Al exhibit high tensile strength in the cast state.

Beryllium bronze or copper beryllium alloys contain between 0.4 to 2% Be. They are one of the highest strength copper based alloys. They combine high strength with non-magnetic properties, and do not generate sparks, with excellent metallurgical properties for forming and machining. There are two families: the first family (C17200 and C17300) includes high strength with moderate conductivity, and the second family (C175000 and C17510) presents high conductivity with moderate strength.

Also, other alloys are commercially available, as copper nickel, which exhibits optimal resistance to corrosion from seawater in marine environments, and nickel silver, which is made of copper, zinc and 10-30% nickel. Its name is due to its pleasing silver color and it exhibits the same level of corrosion resistance and strength as other brasses.

In the following section we will learn more about the characteristics, heat treatments, physical and mechanical properties, and applications of some commercial copper-based alloys that present particular properties belonging to the families of aluminum bronzes and beryllium bronzes.

3.- Age-hardenable Cu-2Be alloy and Cu-9Al-4Fe aluminum bronze

Copper beryllium alloys (Cu-2Be) are precipitation hardened alloys, which exhibit high strength and hardness, low anelastic behavior, fatigue endurance, high corrosion resistance, good electrical and heat conductivities, and non-magnetic properties. They are widely used in flexure elements and sensors in high accuracy measuring devices, high precision electronic components, key components for the aerospace industry non-sparking tools, and injection molding, among others [Montecinos and Tognana, 2024]. There are two types of Cu-Be alloys, depending on the beryllium content. The high strength Cu-Be alloy contains between 1.6 to 2.0% Be and high conductivity Cu-Ni-Be (or Cu-Co-Be) alloy contains between 0.2 to 0.8% Be and 1.4 to 2.5% Ni (or Co) [Guoliang et al., 2021; Zhang et al., 2021; Zhou et al., 2016]. The most widely used commercial alloy is high strength Cu-(1.8-2.0)% Be alloy, which is assigned as C17200 according to UNS, and usually contains impurities of Co, Si, Fe, and Ni [Montecinos et al., 2022].

The alloy Cu-9Al-4Fe is a two phases aluminum bronze, which is known as SAE68A. These are alloys that exhibit high toughness, high tensile strength, abrasion, wear, impact, and good fatigue resistance, besides of high corrosion resistance in seawater [Duncheva et al., 2022; Wu et al., 2015]. Their erosion-corrosion resistance makes these alloys used for making large-size and high rotating speed propellers [Song et al., 2020; Wu et al., 2015]. Besides, it is a suitable material for sliding bearing bushings under increasing impact and alternating loads in aggressive environments [Duncheva et al., 2022].

3.1.- Microstructural characterization of homogenized samples

Samples were provided by Roberto Cordes S.A. as 10 mm diameter bars. Slides were cut using an Isomet Speed Saw with a diamond disc, and the specimens were homogenized for 30 minutes at 830°C and quenched into water at room temperature. The micrographs were taken using a Leica DMI3000M microscope on specimens previously electropolished in a satured solution of chromium trioxide in phosphoric acid for a few second at 4 V, and then immersed in a ferric chloride solution.

Figure 2 shows micrographs of homogenized samples of a polycrystalline Cu-2Be alloy and a polycrystalline Cu-9Al-4Fe alloy. Cu-2Be homogenized sample (Figure 2(a)) is a matrix of α phase (fcc Cu solid solution), with a grain size of around 30 µm, and the presence of twins and some primary beryllides within the grains. A detailed characterization of the microstructure of homogenized Cu-2Be samples was reported in ref. [Montecinos and Tognana, 2024]. Cu-9Al-4Fe homogenized sample contains α, β' and intermetallic κ phases. α is Cu solid solution phase, β' is $AlCu_3$ phase with martensitic structure, and κ are iron-enriched phases [Song et al., 2020; Wu et al., 2015; Xu et al., 2022].

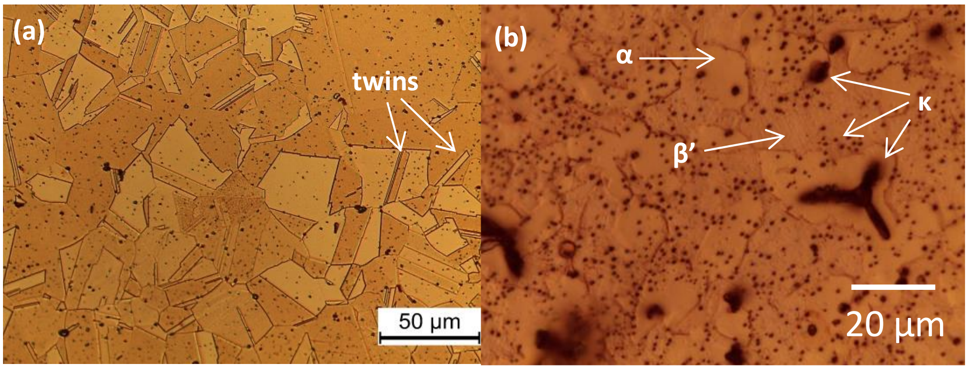

Figure 2. Representative optical micrograph of homogenized Cu-2Be (a) and Cu-9Al-4Fe (b) samples.

3.2.- Mechanical properties

In order to analyze and compare the mechanical properties of the copper-based alloys studied, microhardness tests and elastic modulus measurements were performed on homogenized Cu-2Be and Cu-9Al-4Fe samples, after being subjected to aging treatments at 400°C for different times. Comparisons were also made with electrolytic copper samples homogenized for 10 min at 800°C, which presented a grain size of 40 µm.

Vickers microhardness measurements were performed using a Mitutoyo MVK-H11 equipment on disks with a thickness of about 2 mm. Samples were prepared using the following methodology: samples were polished with a 1000 grit emery paper, 3 µm diamond and 1 µm alumina powder, and then they were cleaned with ethanol spray and dried with air. Ten indentations were made on each sample under a load of 300 g and a holding time of 10 s. The elastic modulus was measured by the Impulse Excitation Technique (IET) under flexural mode and using a specifically developed device. More details of this technique can be obtained from ref. [Montecinos et al., 2016]. Samples with rectangular prism geometry, a section of around 8 mm x 3.5 mm and a length of 65 mm were measured. The vibration excitation was done by the impact of a small ball in the center of the sample, and the received signal was recorded by a commercial microphone, an amplification system and a digital oscilloscope.

Figure 3 shows the mechanical properties, microhardness and elastic modulus, of homogenized samples of electrolytic copper (Cu), Cu-2Be and Cu-9Al-4Fe alloys. Copper exhibits a hardness of less than 50 HV, while the addition of beryllium makes the Cu-2Be alloy exhibit a hardness of almost 100 HV, and the Cu-9Al-4Fe alloy exhibits a hardness of 170 HV (Figure 3(a)). As was mentioned above, Cu-2Be alloy is an age-hardenable alloy that can exhibit high hardness and strength due to the formation of metastable nanoprecipitates by aging treatments from α phase at temperatures between 280 and 400°C [Chakrabarti et al., 1987; Rioja and Laughlin, 1980; Tang et al., 2017; Zhang et al., 2021]. The sequence of precipitation has been studied, and the formation of the following metastable phases prior to the equilibrium γ phase has been recognized [Chakrabarti et al., 1987; Rioja and Laughlin, 1980]: formation of Guinier-Preston zones, γ'' phase, and γ' phase. Figure 3(a) shows the hardness curve of the Cu-2Be alloy after being subjected to an aging treatment at 400°C. The highest hardness of 354 HV is reached after an aging treatment of 45 minutes at 400°C, which, according to previous studies, would be due to the formation of γ' nanoprecipitates [Guoliang et al., 2012; Montecinos and Tognana, 2024; Montecinos et al., 2017; Rioja and Laughlin, 1980; Yagmur et al., 2011; Zhang et al., 2021; Zhou et al., 2016]. For longer aging times, γ' phase would undergo continuous variations with respect to its crystalline structure, misfit angle, and an elongation of the precipitates, reaching stable γ phase at long times [Montecinos and Tognana, 2024]. The slight decrease in hardness for aging times longer than around 1 h would be associated with these changes. Through the formation of γ' nanoprecipitates, a hardness of almost 10 times that of electrolytic copper and more than twice that of the homogenized Cu-9Al-4Fe alloy is obtained. Figure 3(a) also shows the hardness values of the Cu-9Al-4Fe alloy aged at 400°C. A slight increase in hardness levels is observed from 170 HV to 200 HV after 15 minutes of aging, a hardness value that remains constant for longer times. According to preliminary results, this increase would be associated with changes in the fraction of phases present.

Regarding the elastic modulus, Figure 3(b) shows that electrolytic copper has a value of almost 120 GPa, while the homogenized samples of the copper-based alloys studied have lower values, around 110 GPa for Cu-2Be and around 90 GPa for Cu-9Al-4Fe. When the alloys are subjected to aging treatments at 400°C, the elastic modulus increases. In the case of the Cu-9Al-4Fe alloy, the elastic modulus exhibits an increase from 90 GPa for around 100 h to 110 GPa for 500 h of aging time. On the other hand, the elastic modulus of Cu-2Be increases from around 110 GPa to values slightly higher than 120 GPa, exceeding the elastic modulus of copper.

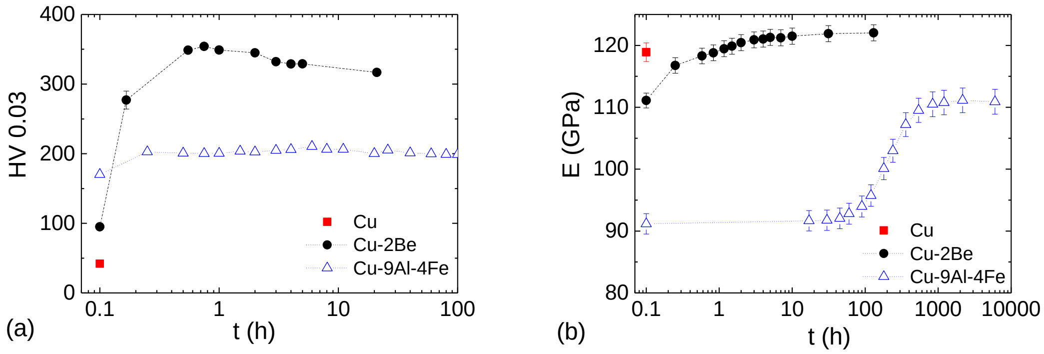

Figure 3. Variation of the hardness (a) and elastic modulus (b) of copper and the studied copper-based alloys subjected to aging treatments at 400°C: Cu-2Be, and Cu-9Al-4Fe. The aging time of 0.1 h corresponds to the homogenized samples.

3.3.- Characterization techniques

To carry out a detailed characterization of the microstructure of copper-based alloys, the most commonly used techniques are optical microscopy and scanning electron microscopy (SEM). By detecting backscattered electrons (BSE), it is possible to differentiate different phases present, due to the production of those electrons differs based on the weight of the elements. Figure 4(a) shows a BSE image of the homogenized Cu-9Al-4Fe alloy, obtained by SEM microscope, model 40XVP at 20 kV. κ phases exhibit a darker color. In order to identify the phases present by estimating the composition of each one, energy dispersive spectroscopy (EDS) coupled with SEM is generally used. The EDS spectrum obtained at the point indicated with the symbol "+" in Figure 4(a) is shown in Figure 4(b). The microanalysis system used was an Oxford X-MAX 50. For the study of nanoprecipitates, such as the metastable phases formed in the Cu-2Be alloy by aging treatments, the transmission electron microscopy technique (TEM) is generally used [Zhang et al., 2021]. Crystallographic techniques such as X-ray diffraction (XRD) are also used to identify the phases present. Small angle X-ray scattering (SAXS) measurements have been used to study the size and shape of the nanoprecipitates formed after aging treatments at different temperatures and times on a Cu-2Be alloy [Montecinos and Tognana, 2024]. For the study of Cu-2Be alloys, there are some difficulties when choosing the correct characterization techniques to use. On the one hand, there is the nanometric size of the phases formed, but there is also the low atomic number of beryllium, which makes it undetectable by some techniques, such as EDS. For this reason, more specific and less common techniques must be used for its study.

Compounds containing beryllium can be analyze using for example X-ray photoelectron spectroscopy (XPS), micro-Raman spectroscopy and Auger electron spectroscopy (AES) [Barr, 1982; Kong et al., 2018; Montecinos et al., 2022; Wang et al., 2015]. However, recent studies have analyzed the use of the Laser-induced breakdown spectroscopy (LIBS) for the in-depth characterization of the oxide film formed after high-temperature oxidation of the Cu-2Be alloy, which also allowed to estimate the thickness of the film formed [Montecinos et al., 2022].

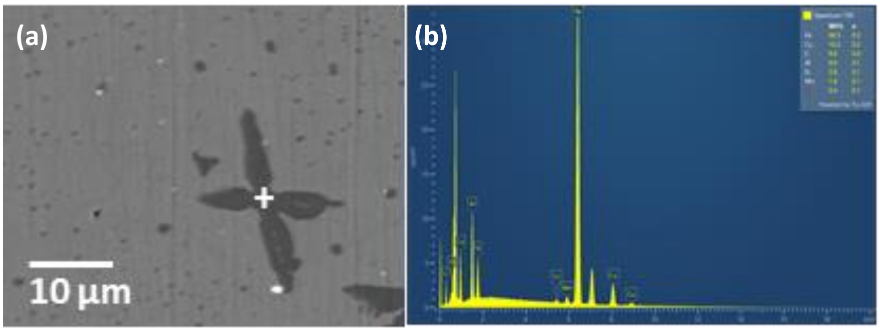

Figure 4. (a) BSE image of the homogenized Cu-9Al-4Fe alloy. (b) EDS spectrum of the point indicated with the symbol "+" in Figure 4(a).

The results presented in this study show how the addition of alloying agents to copper affects the microstructure of the material and the mechanical properties, in particular its hardness and elastic modulus. Furthermore, it is possible to modify the microstructure of the material by means of aging treatments, in order to form nanoprecipitates that greatly harden the material or to modify the fraction and characteristics of the phases present, producing improvements in the mechanical properties. The selection of the required material and heat treatments to be performed are highly dependent on the specific application and the requirements imposed on the material. On the other hand, for the study of these materials, different aspects must be considered, such as the size of the phases present and the ability to detect the elements constituents. In particular, the study of aged Cu-2Be alloys requires careful studies, due to the nanometric size of the precipitates and the low atomic number of Be.

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