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LIMITATIONS FOR WIDER USAGE OF GOLD-ALUMINUM ALLOYS BASED ON INTERMETALLIC COMPOUND Au-Al_2

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Abstract

Gold and golden alloys have had remarkable applications in many fields, through the entire human history. Many alloys were chosen according to their mechanical properties, and good anticorrosive properties, while color was rarely of importance in most industrial materials, except for bronze, stainless steels or nickel alloys. A common limitation for a wide use of golden alloys lies in their high price, while the alloys from Au-Al system should not be an expensive alloy, anyway. One specific advantage comes from one golden alloy which shows an intriguing violet color, as a result of the presence of an intermetallic $AuAl_2$ compound. This alloy, composed of 79%Au and 21%Al, shows good anticorrosive properties, but also critical mechanical properties, namely pronounced brittleness, which is a serious drawback in its use. From this point of view the casting is preferred over shaping by any metal working/deformation method.

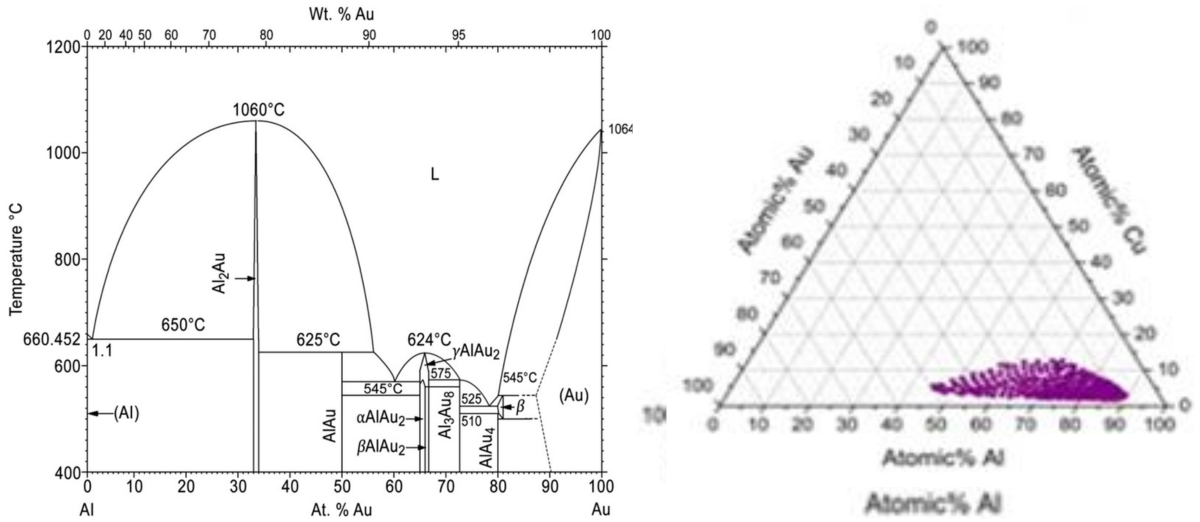
Keywords: *Au-Al_2 compound, decorative properties, brittleness, casting*

1. INTRODUCTION

Gold and copper are well known metals from the antique times, while aluminum is discovered much later. Gold always was and still is an expensive metal, but copper and aluminum are not, as well as zinc. It is well known that alloying (of gold) is provided not only for lowering the price, but for improving the strength of such alloy, with changing the other desired properties (thermal, electrical, color, density, etc.) [1]. One of the ways to strengthen an alloy is based on the possibility of forming an intermetallic compound, if it is possible in such an alloying system [2,3].
By changing the properties of a metal through the introduction of one or more elements to form an alloy, new fields of application may be expected. Here, some important properties and limitations of an alloy from the Au–Cu–Al system, known for its violet color, will be analyzed.

2. COLORS OF Au-Al ALLOYS

Pure gold is a shining yellow metal, while aluminum is bright white. The yellow or white golden alloys are pretty well known, while other colored golden alloys as blue, green, or black, are less known. One of the less known golden alloy is violet in color, which belongs to the Au-Al system. The phase diagram Au-Cu is well investigated, but this could not be said for Au-Al system. n this system, more than one intermetallic compound can be found (Fig. 1a). Among these compounds, $AuAl_2$ possesses the highest melting temperature, similar to that of gold, and also the highest thermal stability [2]. Not all intermetallic compounds have the same color; for example, the intermetallic compound Au_5Al_2 is white, while $AuAl_2$ is purple. Both compounds are pretty brittle, and they create so called *plague*. The $AuAl_2$ compound forms within a narrow concentration interval (Fig. 1a); see also the diagram in Fig. 1b for the Au–Cu–Al alloying system.



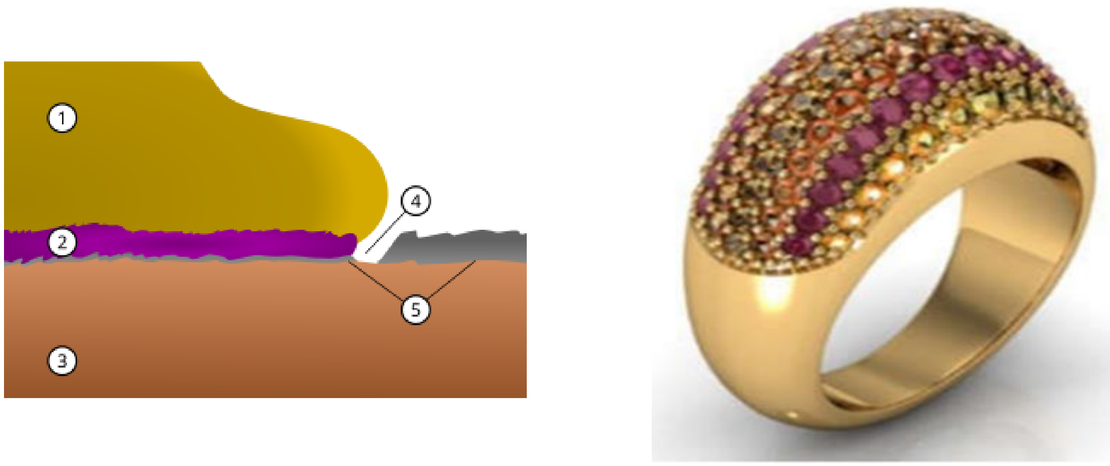
a) b)

Figure 1. (a) Au–Al phase diagram, and (b) concentration region for violet-colored alloys in the Au–Cu–Al system

The mentioned intermetallic compounds are poor electrical conductors, but during solidification they cause the reduction in volume. Such behavior usually creates the gap between gold and aluminum, causing the mechanical failure at the joint [2-7].

3. TWO EXAMPLES OF APPLICATION

Gold–aluminum alloys still do not have significant applications, so they may be used for specific purposes. Two typical examples from electronics and jewelry are presented in Fig. 2.



a) b)

Figure 2. Two applications of violet gold alloys: a) in microelectronics for brazing (violet color between gold and aluminum) and b) for decoration purposes in jewelry

**In Fig. 2a): 1- gold wire, 2- purple plague, 3 - copper substrate, 4- gap eroded by wire-bond and 5- aluminum contact*

In the gap (4) between gold (1) and copper (3), a violet alloy (2) is formed by the addition of aluminum (5). This behavior has attracted further investigations into diffusion and atomic-level migration. Mechanisms for alloy strengthening in the Au–Cu system have been studied much more thoroughly [9] than those in the Au–Al system.

From the another point of view, it is practically established that making a jewelry product using only the violet Au-Al alloy is impossible, because this alloy does not possess satisfactory mechanical properties, so it should be used only as inlay or similar decoration techniques in jewelry.

Decoration at one gold ring, as shown in Fig. 2b), is provided by 3D printing when various gold alloys were applied in different colors. The phenomenon of producing a gap, with reduced strength but increased brittleness at a joint, is known as the *purple/violet plague*. Atomic diffusivity in this case primarily occurs when gold and aluminum thin sheets are in contact. A more detailed study is needed at an academic level, particularly through the Kirkendall effect [3,6], for numerical modeling.

4. VOIDING IN GOLD-ALUMINIUM ALLOY AND DISCUSION

Voids, or voiding, are essential for ensuring the homogeneity of any material, meaning they enable the full properties of a product or structure. Voiding has been well studied in sintered materials but less so during welding or brazing, as is the case with the $AuAl_2$ violet alloy.

For alloys in the Au–Al system, some efforts have been made to investigate atomic migration caused by the Kirkendall effect, which can lead to the formation of voids (or porosity). This effect in the Au–Al system was first observed in microelectronics (during wire bonding), as suggested in Fig. 2a, where the intermetallic compound $AuAl_2$ forms at the contact between the two metals through a diffusion mechanism [5–6]. Such reactions are the subject of study in physical metallurgy [3], where mathematical approaches to diffusivity and related phenomena are Many experiments have shown that the element with the lower melting point—in this case, aluminum—diffuses faster [2,3] than gold. This behavior is not observed only in alloys where solid solutions are formed, such as in brass. If atomic diffusion in an alloy leads to the formation of voids, the strength will be reduced, while brittleness is increased, making mechanical failure of the joint more likely.

Voiding during the formation of the intermetallic compound causes a reduction in volume, possibly creating a gap at the Au–Al interface (see Fig. 2a). It is worth mentioning that the formation of this gap obviously reduces other properties, such as electrical conductivity, specifically at the interface.

Such behavior is observed in alloys composed of the metals Au, Cu, and Al (see Fig. 1a), which crystallize in a face-centered lattice and are all known as ductile metals, meaning metals with high toughness. This example shows that every alloying process, such as the formation of $AuAl_2$, must be carefully monitored, even when soft metals are used. It is worth underlining that these soft metals are not brittle in their pure state.

Similar disintegration in metals was first observed in tin (also known as "tin disease," tin pest, or tin leprosy), when an allotropic conversion from white to grey tin occurred at lower temperatures [3], accompanied by significant changes in properties. However, the $AuAl_2$ compound is not formed through a solid-state phase transformation mechanism (see Fig. 1a).

Such behavior may influence the production schedule of the violet Au-Al alloy. To avoid undesirable effects, longer heating for atomic diffusion can be minimized by using 3D printing, with the final product shown in Fig. 2b. The 3D welding technique is quite fast, meaning it does not require much time, and the nicely colored golden balls can be successfully joined to the parent metal—of course, only as decorative elements. For the 3D welding method, the desired metal is used in wire form, and there is no need to apply any kind of flux, which is a very common practice in many brazing or soldering technologies. Such fluxing materials (in any form) may be a source of gas bubbles, which can lead to defects in the solidified metal.

The 3D machine in this case utilizes arc welding, possibly with a laser beam [9], based on CAD drawings, enabling the production of versatile, complex, and high-quality metal products—one of which is shown in Fig. 2b. This technique allows easy changes of cladding materials, as seen in the rows of very small balls in various colors in the same figure; however, all of these colored balls were made from the same gold content. The production of the ring shown in Fig. 2b using any casting or classical foundry method [10] would be practically impossible.

5. CONCLUSION

Golden alloys are often produced in various colors, especially for jewelry making. In industry, however, this demand is never of primary interest; price and other useful properties are more important. Alloys from the Au–Al system might be significant due to the low price of aluminum compared to gold. Furthermore, the Au–Cu–Al ternary alloys have not been studied as extensively as the Au–Cu–Zn system.

Intermetallic compounds, in general, may have an important influence on metal properties and, consequently, on their applications. With respect to the properties of the $AuAl_2$ compound, it serves as a good example for studying its attractive violet color but poor brittleness. In this case, the "violet plague" of the Au–Al_2 alloy becomes very important for understanding its limited uses, such as in electronics and jewelry.

The formation of an intermetallic compound from gold and aluminum at the interface, as the violet plague, is shown in Fig. 1a at position (4). This violet plague is, however, the main limitation for the wider use of such an intermetallic compound between gold and aluminum. The violet $AuAl_2$ alloy may be used in jewelry only as an inlay or in similar decorative methods, but not for components or products exposed to tensile or impact loads/stresses.

Given these limitations, the use of this attractive but brittle violet alloy from the Au–Cu–Al system cannot be recommended, especially for structural applications in industry.

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