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# The growth and tensile deformation behavior of the silver solid solution phase with zinc

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ABSTRACT

The growth of homogeneous silver solid solution phase with zinc are conducted at two different compositions. X-ray diffraction (XRD) and Scanning electron microscope/Energy dispersive X-ray spectroscopy (SEM/EDX) are carried out for phase identification and chemical composition verification. The mechanical properties of silver solid solution phase with zinc are evaluated by tensile test. The engineering and true stress vs. strain curves are presented and analyzed, with those of pure silver in comparison. According to the experimental results, silver solid solution phase with zinc at both compositions show tempered yield strength, high tensile strength and large uniform strain compared to those of pure silver. Fractography further confirmed the superior ductility of silver solid solution phase with zinc at both compositions. Our preliminary but encouraging results may pave the way for the silver based alloys to be applied in industries such as electronic packaging and structure engineering.



## 1. Introduction

Silver was firstly mined in about 3000 B.C. in Anatolia (modern day Turkey) [1]. In ancient days, most silver and alloys were used to fabricate coins, bullion and silverware. Nowadays, silver and its alloy still have innumerable applications in arts, science, jewelry, decor, industries, and beyond. According to the report from relevant institute [1], over half of the silver was committed to industrial fabrication in recent five years. The continuing demand of silver in the industry is due to its unique properties such as the best electrical and thermal conductor among metals, high reflectance of light, and the ability to endure high temperature. In history, silver and its alloys have been utilized as filler materials in brazing processes [2,3] in industries, and recently as bonding media in electronics [4,5]. These silver-based joints were reported to be strong, leak-proof, and anti-corrosion. On the other hand, the mechanical properties of silver alloys, such as tensile strength and plasticity, have little been investigated probably because they were not considered as a structural material. With numerous new applications rising on the horizon, the mechanical properties of silver alloys become even more important. For example, in electronic packaging, silver alloys have been proposed as alternative materials for bonding wires [6]. The bonding wires need to have not only good thermal and electrical conductivity but also sufficient tensile strength and elongation [7]. Moreover, the improvement in mechanical properties of silver may not only enhance its performance in traditional applications such as brazing but also exhibit the potential to be utilized in structure engineering. Recently, the Ag-Pd [8] and Ag-Au-Pd [7,9] systems have been reported to have better tensile strength and elongation than pure silver. However, the addition of gold and palladium increases the cost of raw materials. Therefore, it is still a challenge to make silver based alloy both strong and ductile while keeping its low cost.

In spite of these facts, alloying is still a strategy to achieve this goal. Solid solution strengthening mechanism has been well known, responsible for increasing the yield strength of metals as the result of the interactions between the solutes and dislocations. According to the Ag-Zn phase diagram [10], which is shown in Fig. 1, the solid solubility of zinc in silver is about thirty atomic percent (30 at%) at 100 °C. This value will be smaller at room temperature but zinc concentration as large as 25 at% was acquired in the literature [11]. The solid solubility is quite substantial which makes Ag-Zn system appear as a promising candidate. In addition, recall that alpha brass, the copper solid solution phase with zinc, is stronger than pure copper and still very ductile and thus suitable for cold working and many other structure attempts [12] Moreover, silver and copper are in the same column in the periodic table and thus have similar valence electron configuration. This gives rise to an interesting question: whether alloying zinc into silver can make the alloy both strong and ductile?

Usually, the total dopant concentration in silver alloys is below

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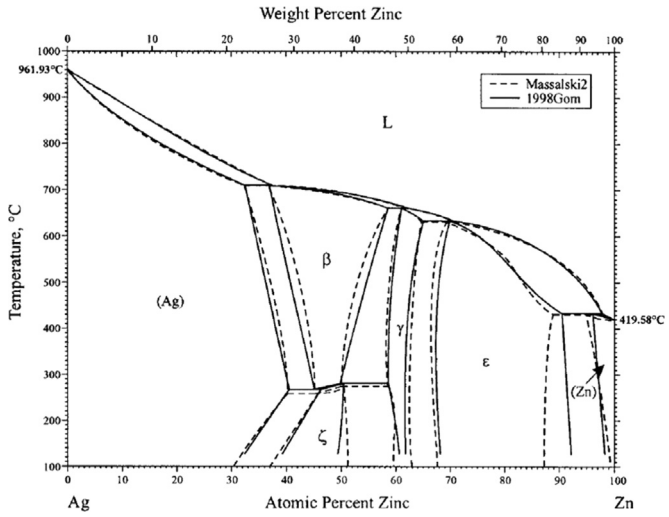


**Fig. 1.** Silver-zinc binary phase diagram.

15 at%, such as sterling silver (Ag-12.1 at%Cu), Ag-Pd [8] and Ag-Au-Pd system [7,9]. As a preliminary study of Ag-Zn system, we chose to grow and characterize silver solid solution phases with 5 at% and 15 at% zinc concentration, respectively, which are designated as (Ag)-5Zn (3.1 wt%) and (Ag)-15Zn (9.6 wt%). Meanwhile, pure silver was used as the controlled group for the following experiments [13].

In the following section, the preparation method of the ingots of (Ag)-5Zn and (Ag)-15Zn and test samples will be firstly presented. Secondly, the process and results of materials characterization will be described. Next, the engineering and true stress vs. strain curve which are acquired in tensile test will be discussed. In addition, the fracture surface of the tensile specimen will be examined by Scanning Electron Microscope (SEM) and the fracture mode and failure mechanism will be analyzed. Lastly, the potential application and scientific value of the research will be discussed.

## 2. Experimental procedures

### 2.1. Preparation of ingots

In our research, the ingots of (Ag)-5Zn and (Ag)-15Zn were prepared by melting raw materials under vacuum. The starting materials were 99.99% silver shots and 5N zinc shots. Next, the shots were uniformly mixed and loaded into a quartz tube with 15 cm in length and 1 cm in inner diameter. While the quartz tube was being pumped by vacuum pump, it was sealed by hydrogen torch at the position which is between the pump end and metallic shots. The vacuum within the capsule can effectively mitigate the oxidation issue and reduce defects such as gas trapped bubble in the final products. Then the capsule was placed into a furnace preheated at 1030 Celsius and kept isothermal for 3 h for adequate homogenization. Lastly, a six-stage cooling profile between 1030 Celsius and room temperature was designed for acquiring homogenous solid solution phase. More specifically, the temperature of each dwell stage was determined by the homologous temperature (Th) which expresses the temperature of material as a fraction of its melting temperature using Kelvin. The materials were cooled down from 0.95 to 0.3 (lower than 100 Celsius) in 8 days and the cooling between adjacent stages were quite fast and done within 2 h.

Disk samples, cut from the ingots by slow speed saw, were ground and polished carefully for material characterization. X-Ray Diffraction (XRD) and Energy Dispersive Spectroscopy (EDX) were

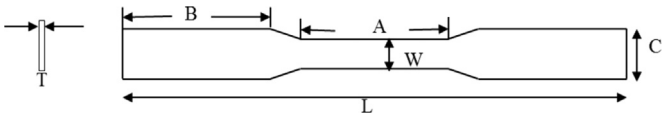


**Fig. 2.** The geometry of tensile specimen, in accordance with ASTM E8/E8M-08.

**Table 1.**
The dimensions of tensile specimen, in accordance with ASTM E8/E8M-08.

| | W | T | L | A | B | C |
|---|---|---|---|---|---|---|
| **mm** | 2 | 1.1 | 33.33 | 10.67 | 10 | 3.33 |
| **inch** | 0.0787 | 0.0433 | 1.3120 | 0.4200 | 0.3937 | 0.1311 |

carried out to verify if the solid solution phase with nominal composition was successfully prepared. Rigaku SmartLab diffractometer was used for phase identification. Tests were conducted by using Bragg-Brentano (BB) optics since the samples are bulk polycrystalline materials. The θ-θ scan was operated at 2° per minute with a filter removing copper k-beta line. FEI XL-30 FEG SEM equipped with EDX system was used for chemical composition analysis. Test areas were randomly chosen from the samples and data was collected from nine points per area in which the average spacing between adjacent points is 75 μm.

The tensile specimens from each ingots were machined by electrical discharge machining (EDM) in accordance with ASTM E8/E8M-08 specification [14]. In Fig. 2 and Table 1, the geometry and dimension are shown respectively. These samples were carefully polished in order to remove surface damage caused by EDM and then annealed at 200 Celsius for 1 h to release residue stress induced by polishing. After annealing process, XRD and EDX were conducted and results were compared to those of disk samples. The uniaxial tensile tests were performed at room temperature by INSTRON 5500R tester with a nominal strain rate of about $10^{-5}\ s^{-1}$. After fracture, the specimens were observed by SEM to reveal deformation morphologies and fracture behavior.

## 3. Results and discussion

### 3.1. XRD and EDX results

XRD results of pure silver, (Ag)-5Zn and (Ag)-15Zn disk samples are shown in Fig. 3. The data collected in the tests were processed and analyzed by PDXL, an integrated powder XRD analysis software package. The peaks in Fig. 3 are indexed and the crystallography information of samples are acquired and listed in Table 2.

From Fig. 3, it is apparent that the crystal structure of pure silver, (Ag)-5Zn and (Ag)-15Zn are face centered cubic (FCC) in terms of diffraction patterns' systematic absence. In addition, there are no impurity peaks other than the peaks of pure silver, (Ag)-5Zn and (Ag)-15Zn in each XRD pattern. Therefore, it is conservatively concluded that the materials composing the disk samples are nearly homogeneous. In Table 2, d is d-spacing between corresponding crystallographic plane, (hkl) is the Miller's indices with classic denotation, and a is the calculated lattice constant by using values of each d-spacing under the assumption that the geometry of lattice is perfect cubic. As results, the weighted average value for lattice constants are 4.0893 Å, 4.0796 Å and 4.0623 Å for pure silver, (Ag)-5Zn and (Ag)-15Zn respectively. The trend of decreasing values for lattice constant is consistence with the right-shifted peaks in XRD patterns, which can be explained by reviewing the atomic radii for silver and zinc elements. The empirical atomic radii of zinc is 134 pm, which is smaller than that of silver's, 144 pm. Therefore, if one silver atom is replaced by zinc in silver lattice, it would result in dent in its crystal structure, which caused