



Physical property of 925 sterling silver metal injection molding and morphology of brown parts under varying solvent-based debinding conditions

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ABSTRACT

This research aims to study the physical properties of raw parts produced using Metal Injection Molding (MIM), an advanced manufacturing process suitable for the industrial-scale production of highly complex, small, and high-precision three-dimensional metal parts. However, applying this technique to precious metals, especially 925 sterling silver, still has significant limitations and research gaps, particularly regarding the use of atomized metal powders, which are a byproduct and have lower costs than general-purpose specialized metal powders. 925 silver feedstock used to produce the MIM samples consisted of 90% 925 silver powder and 10% binder. Solvent-based binder removal was performed in water for 5 hours at three temperatures: 30°C, 40°C, and 50°C, respectively. Microstructure and particle morphology were examined using a scanning electron microscope (SEM). The goal was to identify the optimal conditions for forming an open porous structure conducive to sintering and shape retention in subsequent industrial processes. The experimental results showed that the optimal material ratio consisted of 90% silver powder and 10% binder by weight, resulting in an average material density of 4.507 g/cm³ and an average material tensile strength of 17.70 MPa. The results indicated that the binder removal process using distilled water at 50°C for 5 hours was the most efficient method.

Keywords: Metal injection molding, Sterling silver, Debinding kinetics, Morphology, Physical properties

INTRODUCTION

Powder metallurgy (P/M) processes involve the production of metal powders, property analysis, and extrusion (or molding) [1-3]. These processes are used to produce metal powders, analyze their properties, and then sinter them to produce finished components. The application of powder metallurgy technology in the Thai gem and jewelry industry shows relatively limited use in manufacturing processes. Thai manufacturers often use it as a powder solder or binder for joining jewelry components [4-7]. However, this process can be applied to a variety of manufacturing processes, such as powder injection molding (PIM), metal injection molding (MIM), and additive manufacturing (AM) [8-10].

In the context of metal injection molding (MIM), which involves the preparation of the injection molding material, part forming, and sintering, the flow behavior of the feedstock, which is a mixture of silver powder and binder, is studied during the material preparation. The rotor speed and preheating temperature are then calculated to achieve the optimal

viscosity. This ensures that the metal flows fully into the mold without causing component segregation. Sintering is a thermal process that bonds individual powder particles together. This is a crucial step in increasing the strength, rigidity, and toughness of the particles for various applications (e.g., compression, tensile, and other conditions). Sintering involves heating the injection-molded part to a temperature close to the melting point of the metal. This sintering temperature causes the internal structure of the particles to move at the atomic level. This results in the dispersion and interconnection of particles. The resulting interparticle adhesion is removed by the binder (Debinding Kinetics): The temperature and time of preheating are usually derived from the melting point and thermal decomposition point of the binder, which must be consistent with the TGA analysis results. This can occur either in the solid state or through the formation of a liquid phase from the material mixture under sintering conditions. Various methods for binder removal exist, including catalytic debinding using a chemical agent, solvent

debinding with a liquid solvent or water, and thermal debinding using heat [11-14].

To study the properties of the various components present in silver alloys in the MIM process, the main process parameters were systematically analyzed to understand the strength required for forming while maintaining the silver luster and to understand better the processing behavior of 925 sterling silver powder [15-19]. The leftover powder from the research of Montri et al. [20], with particle sizes in the range of 75-100 μm , was used as the raw material. This research aims to evaluate the physical properties of 925 sterling silver parts produced by the MIM process. Process parameters: type of solvent, temperature, time, solid-to-liquid ratio and stirring method, binder removal rate, percentage weight loss versus time and temperature, and determining the optimal separation conditions for dissolving water-soluble binders from MIM raw parts, thus strengthening Thailand's potential to be a regional hub for the production and trade of high-value precious metals.

MATERIALS AND METHODS

Materials and production of metal powder

The material used in this study was 925 sterling silver alloy prepared according to the Thai Industrial Standard (TIS 21-2515). The alloy composition was obtained by mixing 99.99% pure silver with 99.9% pure copper in a ratio of 92.5:7.5 by weight. Metal powder production was done using a prototype gas atomizer at Rajamangala University of Technology Isan, as shown in Figure 1. This gas atomizer consists of various components and operates using nitrogen gas as a medium to atomize the molten metal into fine droplets. The nozzle used in the experiment was a close-fitting nozzle. After mixing the metal for the specified time, the nozzle was lifted to allow the molten metal to flow into a water tank located below the melting chamber. Samples were collected for further testing.

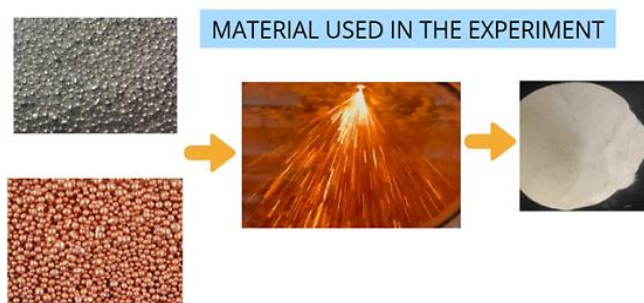


Figure 1 Material used in this study 925 sterling silver alloy powder.

Binder composition, feedstock preparation and metal injection molding

The 925 silver powder, with a particle size of 75-100 μm obtained from gas atomization, was used as the base material. The binder system was formulated to ensure adequate flowability during injection molding, shape retention during debinding, and ease of removal prior to sintering. Based on our previous work [21], the binder consisted of high-density polyethylene (HDPE) as the backbone polymer, polyvinyl alcohol (PVA) and polyethylene glycol (PEG) as water-soluble binders, paraffin wax (PW) as a flow-promoting agent, and stearic acid (SA) as a lubricant and surfactant. The binder composition by weight was 38 wt.% HDPE, 3.75 wt.% PVA, 1.25 wt.% PEG, 54 wt.% PW, and 3 wt.% SA. Feedstock preparation was performed using an internal mixer. The 925 sterling powder was thoroughly mixed with the binder materials in various proportions ranging from 1 wt.% to 10 wt.% binder, with the remainder being silver powder. First, the 925 silver powder was preheated to 60°C for 15 min at a rotor speed of 10 Hz, except when using HDPE, which required 15 Hz. Subsequently, the binder components SA, PW, and HDPE were added sequentially, with each addition lasting 10 min. PVA and PEG were introduced simultaneously at 150°C with a rotor speed of 15 Hz, followed by continued mixing for 20 min to ensure homogeneous dispersion of the powder within the binder matrix. Finally, the heater was turned off while the mixing process continued for 90 min, after which the feedstock was cooled to room temperature and granulated for ease of feeding into the injection molding machine.

Metal injection molding was carried out using a ram injection machine under constant injection pressure of 150 bar and a barrel temperature at the extruder of 190°C, with a holding time of 30 s and a cooling time of 150 s. After cooling, the mold was opened, and the parts were ejected. The injection pressure must be high enough to fill the mold cavities, and the as-molded parts, referred to as "green parts," must have sufficient green strength to maintain their shape and withstand handling loads throughout the debinding and sintering processes, as shown in Figure 2.

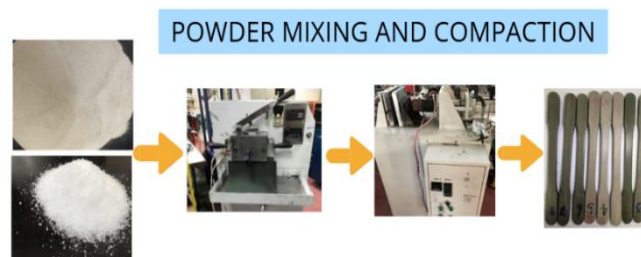


Figure 2 Gas atomized silver powder and binder material, feedstock preparation using an internal mixer, and metal injection molding.

Particle shape analysis and physical property measurement of debound parts

1. Particle shape analysis by Scanning Electron Microscope (SEM), Thermo Scientific, Model: Apreo 2 SEM

The shapes of the metal particles were examined using a scanning electron microscope (SEM). The obtained gas-atomized metal powders have a spherical or near-spherical shape, as shown in Figure 3, which is advantageous for powder injection molding because of improved packing density and flowability. High-magnification observations revealed that the particle surface exhibited a dendritic structure.

2. Physical property evaluation

The density of the MIM green parts was determined using Archimedes' principle, which states that the buoyant force acting on an object immersed in fluid is equal to the weight of the fluid displaced by the object. The mass of the samples was weighed in air and distilled water using a balance with 0.0001 g resolution. The density ρ (g/cm³) can be calculated using the following equation [22]:

$$\rho = \left(\frac{A}{A-B} \right) (\rho_0 - \rho_l) + \rho_l, \quad (1)$$

where ρ is the density of the sample, A is the mass of the sample in air, B is the mass of the sample in the auxiliary liquid, ρ_0 is the density of the auxiliary liquid, and ρ_l is the density of air (0.0012 g/cm³). For this study, distilled water at room temperature was used as the auxiliary liquid, with a density of 0.998 g/cm³.

Solvent debinding

Metal injection molding consists of four main steps: feedstock preparation, injection molding, debinding, and sintering. This study focused on determining the optimal conditions for solvent-based binder removal of 925 sterling silver components. To determine the optimal debinding conditions for 925 sterling silver components, the study used three temperature levels and one time level, as shown in Table 1. Debinding was conducted by immersing the molded "green" parts in distilled water to dissolve the water-soluble binder components. Solvent debinding was performed for 5 h at three different temperatures: 30°C, 40°C, and 50°C. These parameters were selected to evaluate the effect of the solvent temperature on the binder removal efficiency. The experiment was repeated 3 times at different temperatures.

Table 1 Conditions for solvent debinding.

Conditions	Temperature (°C)	Time (hours)
1	30	5
2	40	5
3	50	5

RESULTS AND DISCUSSION

Particle shape of 925 sterling silver metal powder

Figure 3 shows SEM microimages of gas-atomized 925 sterling silver powder under different overheating conditions. The atomized powders exhibited similar characteristics: when gas-atomized, the small metal droplets easily transformed and dispersed better than in highly viscous metal solutions. The effects of overheating the molten metal and peak angles could be observed using scanning electron microscopy (SEM). The size of the gas-atomized silver particles ranged from 75-100 μ m. The resulting silver powders had a variety of shapes [23, 24]. Shapes observed with scanning electron microscopy (SEM) included: plate-like or thin sheet, fibrous, spherical, and irregular. The produced particles were spherical to nearly spherical, with a wide range of sizes. In addition, slight variations in particle shape were found, such as slight irregularity or fibrousness, but these were much less frequent compared to spherical particles. These observations are consistent with the findings of [25,26]. Different experimental conditions resulted in spherical or nearly spherical metal powder particles.

PARTICLE SHAPE OF 925 STERLING SILVER METAL POWDER

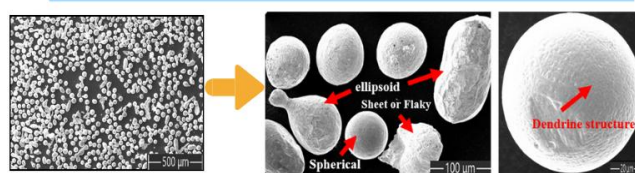


Figure 3 SEM micrographs of 925 sterling silver particles.

Physical property of MIM green parts

The green density of the injection-molded specimens was determined using Archimedes' principle, according to equation 1: the mass of the object lost in water is equal to the mass of water displaced by the object. Therefore, the density of each specimen was calculated from its measured mass in air and in water, as described in the previous section. Figure 5 presents the average green density values obtained from five specimens for each feedstock composition. The results indicate that the green density varied inversely with binder content, which is consistent with the findings of Sasitorn Pramakhmo et al [21]. The feedstock with the lowest binder content, 2 % binder (corresponding to 98 % 925 sterling silver powder), exhibited the highest green density of 6.558 g/cm³. This is attributed to the higher volume fraction of the high-density silver powder ($\rho_{925Ag} = 10.37$ g/cm³) in this composition. As the binder content increased from 2 % to 30 %, the green density progressively decreased. [27] This trend is due to the lower density of the main binder constituents,

paraffin wax ($\rho_{PW} = 0.91 \text{ g/cm}^3$) and high-density polyethylene ($\rho_{HDPE} = 0.95 \text{ g/cm}^3$), compared to that of the silver alloy. Higher binder fractions therefore reduce the overall packing density of the feedstock, leading to lower green densities after molding, as shown in Figure 4.

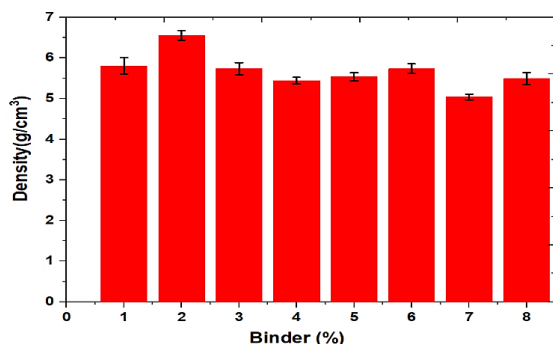


Figure 4 Green density of MIM 925 sterling silver specimens as a function of binder content.

MIM parts and binder removal behavior

The most commonly used method is extrusion molding, with standard test specimens conforming to ASTM E8/E8M-11 standards selected. [28] 925 silver behaves similarly to industrial heavy metals in the MIM process as it is an “alloy” that relies on atomic diffusion during annealing, has similar shrinkage levels, and, importantly, the copper content in this alloy requires oxygen control. [29-30] Solvent debonding involves immersing the specimen in a solvent for a period of time to allow the binder to dissolve and evaporate from the specimen (debonding process), which is controlled by gas diffusion and heating rate. Selected test specimens are shown in Figure 5.

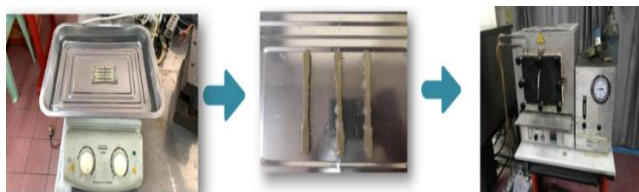


Figure 5 Sample of solution removal and atmosphere metal oven.

In powder injection molding (PIM) processes, multi-component binder systems typically consist of a water-soluble main binder such as polyethylene glycol (PEG) and an insoluble main binder such as polyvinyl butyral (PVB) or polymethyl methacrylate (PMMA). Research by Hwang et al. [31] showed that a binder system containing PEG, when removed at temperatures of around 40-50 °C, reduces the surface tension and viscosity of the solution within the porous structure, resulting in orderly particle shrinkage and preventing the formation of large air gaps (pore clustering). Thus, experiments showed that increasing the temperature from 30 °C (condition 1) to 40 °C (condition 2) and up to 50 °C (condition 3) improved

efficiency. However, temperature increases in this range often resulted in a decrease in the average pore size or a more uniform pore fineness. These results are shown in Figure 6.

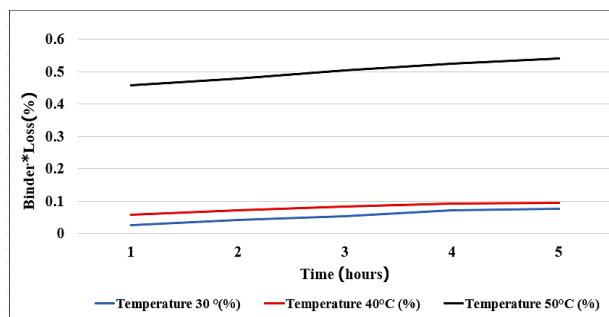


Figure 6 Percentage of binder dissolution as a function of debinding time for MIM 925 sterling silver specimens under three solvent debinding conditions.

Microstructure of the test piece after solvent debonding

The internal microstructures of the green specimens after solvent debinding were investigated to evaluate the influence of debinding temperature on the porosity and pore distribution of the fast-solidifying alloy powder compacts. Distinct solidification structures evolved, governed primarily by the alloy composition and specific solidification parameters. The specimens were extracted by immersion in distilled water for 5 h at various temperatures, followed by drying at 100°C for 1 h to remove residual moisture. Microstructural observations (Figure 7) reveal that the progressive dissolution and diffusion of the water-soluble binder generate continuous pore networks along the extraction pathways. This interconnected porosity acts as critical escape routes, allowing gaseous degradation products to safely permeate and vent during subsequent thermal debinding without causing structural defects such as bloating, blistering, or cracking. Significant morphological differences in the pore structure were observed across the three debinding temperatures [32-33]:

In conclusion, the solvent debinding temperature plays a critical role in determining the pore architecture and binder extraction efficiency of fast-solidifying alloy powder specimens. Increasing the water bath temperature from 30°C to 50°C transitions the pore structure from isolated, large voids to a highly uniform and interconnected network of fine pores. This structural transformation is attributed to the thermally activated diffusion kinetics of the soluble binder. The formation of a well-distributed, interconnected pore network at 50°C successfully establishes low-resistance pathways for gas transport. [34] Consequently, this optimization of the solvent debinding stage ensures safe, defect-free gas venting during subsequent thermal processing, representing a critical parameter

for maintaining structural integrity in high-quality powder metallurgy applications.

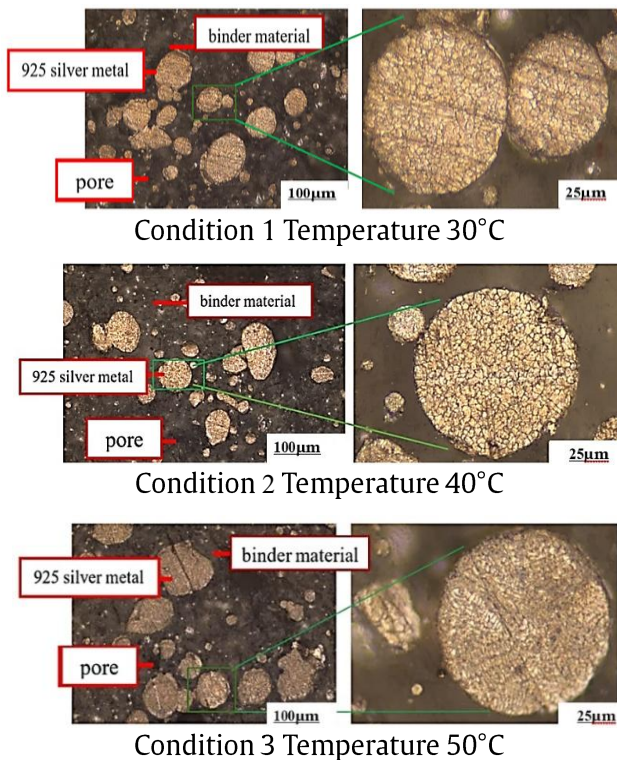


Figure 7 Optical micrograph of the cross-section of the MIM 925 sterling silver sample after solvent separation under conditions.

CONCLUSIONS

In this study, waste 925 sterling silver powder (75–100 µm) produced by gas atomization was used to fabricate parts via metal injection molding (MIM). This study aimed to examine the physical properties of MIM-fabricated 925 silver parts and to investigate the influence of solvent-based debinding temperature on binder removal efficiency and molded-part morphology. Three debinding conditions (30°C, 40°C, and 50°C) were evaluated over a 5 h solvent immersion period. The green density, binder loss, morphology, and pore formation were analyzed to determine the optimal debinding conditions. Based on the experimental results, the following conclusions can be drawn. (1) Scanning electron microscopy (SEM) analysis of the particle morphology revealed that the gas-atomized powders were predominantly spherical or near-spherical in shape, with a fine dendritic surface substructure. This is because the metal droplets cool faster than under equilibrium conditions under the different experimental conditions. As the pouring temperature increased, the viscosity of the metal solution decreased, increasing the mass flow rate. (2) Binder removal behavior was examined through solvent debinding in distilled water at three temperatures: 30°C, 40°C, and 50°C for 5 h. The water-soluble binder components, polyvinyl alcohol (PVA) and polyethylene

glycol (PEG) were progressively removed as the debinding temperature increased. The test samples exhibited varying porosities, with 50°C being the optimum temperature for binder removal. (3) The morphological and microstructural features observed with optical microscopy after debinding show that solvent debinding at 50°C results in fine pores uniformly distributed across the cross-section of the sample, which is conducive to subsequent thermal debinding and sintering. Conversely, lower temperatures resulted in fewer and larger pores, indicating less efficient debinding. Although the binder was completely dissolved at 50°C, some binder residue remains, highlighting the need for further thermal debinding to ensure its removal. Further temperature increases might lead to better results.

DECLARATION OF AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the author used ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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