Effects of dispersion technique and component ratio on densification and microstructure of multi-component Cu-based metal powder in direct laser sintering

Dongdong Gu*, Yifu Shen

Abstract

A multi-component Cu-based metal powder, which consisted of a mixture of Cu, CuSn, and CuP, was developed for direct metal laser sintering (DMLS). The effects of powder characteristics such as particle shape, particle size and its distribution, and dispersion uniformity on the sintering behavior were studied. It is found that using a homogeneous powder mixture produced by ball mixing coarse and fine powders with a broad particle size distribution could increase the original density of the loose powder and, thus, the densification and microstructural homogeneity of the laser sintered powder. The influence of the binder (CuSn) content on the densification and the resultant microstructures of the laser sintered samples were also investigated. It shows that with increasing the amount of the binder, the microstructure became denser. However, at a high content larger than 50 wt.%, the densification showed a decrease, because of the “balling” effect.

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Keywords: Direct metal laser sintering (DMLS); Rapid prototyping (RP); Cu-based metal powder; Powder dispersion; Liquid phase sintering

1. Introduction

As an important branch of rapid prototyping (RP), direct metal laser sintering (DMLS) possesses the capability of fabricating complex shaped three-dimensional (3D) parts directly from metal powder with minimal or no post-processing requirements such as furnace densification cycles or secondary infiltration steps [1]. The combination of high design flexibility, excellent process capabilities, and time- and cost-saving features makes this technique more attractive to industrial manufacturers [2]. Up to now, DMLS has been widely used to create fully dense, durable, and functional metal parts for both prototype and production applications and to build high quality tools with complex feature details for injection molding and die casting applications [3,4].

Generally, the metal powder systems that have been investigated for DMLS can be classified into three main categories: single-component powder, pre-alloyed powder, and multi-component powder [5,6]. Early experiments on laser sintering of the single-component powder such as Ni, Cu, Pb, Sn, and Zn [5,7] have demonstrated that it was unsuitable for DMLS. Since DMLS is characterized by the extremely short time of laser-powder interaction, typically between 0.5 and 25 ms on any powder particle [5], it can only be realized by liquid phase sintering. For the single-component powder, the liquid phase presents owing to the surface melting of particles, and, accordingly, the powder is sintered by joining of non-melted cores of particles via liquid “bridge”. Thus, the requirements for adjusting laser processing parameters are extremely strict in order to ensure not complete but merely surface melting of particles [6]. However, “balling” phenomena are inevitable in this instance due to higher viscosity and surface tension effects, resulting in a large amount of porosity in the sintered structure [7].

To alleviate “balling” effects and improve sinterability, a multi-phase powder approach has been designed by using a pre-alloyed powder system in which melting occurs over a temperature range, or a powder mixture of various components with different melting points [5]. In the case of pre-alloyed powder, the liquid phase arises when the sintering temperature is between the solidus and liquidus temperatures, and the resulting mixture of solid and liquid phases leads to super-
solidus sintering [8]. In the case of multi-component powder, melting one of the components with lower melting point (so-called the binder) forms the liquid phase, and, subsequently, this liquid phase bonds the component with higher melting point (so-called the structural metal) [7]. So far, considerable research efforts have been focused on direct laser sintering of the pre-alloyed powder and the multi-component metal powder. Pre-alloyed powder systems that have been investigated include Ti6Al4V [1], bronze [5,9], and steels (stainless steel [10,11], high speed steel [12,13], low carbon steel [14], and tool steel [15,16]). Multi-component metal powder systems such as Fe–Cu [6], iron–graphite [17,18], Fe–C–Cu–Mo–Ni [19], Fe–Ni–Cu–P [20], Ni–bronce–CuP [4,5], Ni–alloy–Cu [6], and Cu–Sn [7]. Cu–SCuP [3,8,21] have also been studied. Most research work focuses on developing feasible materials and investigating fundamentals of the laser sintering process such as the microstructural evolution, the sintering mechanism, and the influence of process parameters [8,18,19]. It has already been understood that the densification mechanism and the attendant microstructural features of the laser processed material depend on both powder characteristics (particle shape, particle size and its distribution, loose packing density, etc.) and laser processing parameters (spot size, laser power, scan speed, scan line spacing, etc.). However, although a wide variety of metal powder systems are currently being investigated, very few materials exclusively for DMLS have been commercially available [3]. Furthermore, due to the complicated nature of DMLS, in which multiple modes of mass, heat and momentum transportation, and, in some cases, chemical reactions might occur, not much previous work has been reported on the basic principles of this process [18]. Common problems associated with DMLS such as “balling” effect, curling deformation, low sintered density, weak strength, and high surface roughness still exist.

Copper and copper alloys are widely used materials owing to their excellent thermal and electrical conductivities, outstanding mechanical properties, ease of material processing, and low cost [8,21]. In this paper, experimental investigations on direct laser sintering of a self-developed multi-component Cu-based metal powder were carried out, and the effects of powder dispersion technique and component ratio on the densification and the resultant microstructural characteristics of the laser sintered powder were investigated.

2. Experimental procedures

2.1. Powder preparation

Electrolytic 99% purity Cu powder, water-atomized CuSn (10 wt.% Sn) powder, and gas-atomized CuP (8.4 wt.% P) powder were used in this experiment. The as-received powder was sieved through a series of mesh size to extract powder of desirable particle size.

The three components were mixed in a conventional horizontal ball mill with a vacuum-pumping system, using stainless steel balls as the dispersing media. In order to avoid large deformation of the starting particles, a low weight ratio of balls to powders of 5:1 and a low rotation speed of 100 rpm were used. For comparison, a simply mechanical dispersion approach was also used. In this case, the components were mixed in the same vessel but without the balls. The weight ratio of CuSn/Cu/CuP and the corresponding dispersion condition of each powder system as prepared are shown in Table 1.

2.2. Laser processing

A DMLS system developed at the China Academy of Engineering Physics (CAEP) was used for the laser sintering experiments. The system consisted of a continuous wave CO2 (λ = 10.6 μm) laser with a maximum output power of 2000 W, an automatic powder delivery system and roller mechanism, and a chamber with atmosphere control.

Rectangular test specimens with dimensions of 45 mm × 20 mm × 10 mm were prepared. When a part was to be built, a steel substrate was placed on the building platform and leveled. Then, a powder layer (0.30 mm in thickness) was spread on the substrate by the roller. Subsequently, the laser beam scanned the powder bed surface to form a layer-wise profile according to the cross-sectional geometry developed from the CAD model of the part. The similar process was repeated until the part was completed. The laser processing was carried out under the following optimal conditions: laser spot size of 0.30 mm, laser power of 350 W, scan rate of 0.04 m/s, and scan line spacing of 0.15 mm. The entire sintering process was performed in air at room temperature.

2.3. Characterization

The size distribution of the particles was measured using a MS2000 laser particle size analyzer. The morphologies of the powders were examined by a QUANTA 200 scanning electron microscopy (SEM). Samples for metallographic examination were prepared according to the standard procedures, and etched with a mixture of FeCl3 (5 g), HCl (10 ml), and distilled water (100 ml) for 30 s. Microstructures were characterized using the QUANTA 200 SEM and an optical microscope. For chemical composition analysis, an EDAX energy dispersive X-ray (EDX) spectroscopy was used. A BRUKER D8 ADVANCE X-ray diffraction (XRD) analyzer was employed in phase identification.

3. Results and discussion

3.1. Powder characteristics

The material system as investigated consists of three components: Cu powder, CuSn powder, and CuP powder. Generally, the Cu powder with higher melting point of ~1083 °C acts as the structural metal during laser sintering, while the pre-alloyed CuSn (10 wt.% Sn) with lower solidus temperature of ~840 °C and liquidus one of ~1020 °C acts as the binder. Phosphorus was added as pre-alloyed CuP (8.4 wt.% P), taking as a fluxing agent to improve the wettability and thus aid in laser processing.

Table 2 depicts the specifications of particle size of the starting components. It can be seen that the powder system was mixed by the coarse Cu powder and the fine CuSn and CuP powder. Such a bimodal mixture with a broad particle size distribution (>60 μm) might lead to an increase in loose packing density than powder systems with a uniform particle size [2]. Generally, a powder system with higher loose packing density is preferred.

<table>
<thead>
<tr>
<th>Table 1 Powder systems prepared with variation of component ratios and dispersion conditions</th>
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<tbody>
<tr>
<td>Powder system</td>
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<tr>
<td>No. 1</td>
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<td>No. 2</td>
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<tr>
<td>No. 3</td>
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<tr>
<td>No. 4</td>
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<td>No. 5</td>
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<td>No. 6</td>
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<td>No. 7</td>
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</table>
in the DMLS process [19]. Furthermore, the fine CuSn and CuP particles in the powder mixture can provide larger surface area to absorb more laser energy, thereby increasing the particle temperature and the sintering kinetics.

Fig. 1 shows the morphologies of the original components. The Cu powder exhibited an irregular structure (Fig. 1(a)). During liquid phase sintering, a torque will exist in such nonspherical particle of Cu powder, which is ascribed to misalignment of the particle center [12]. The torque tends to rotate the particles in the liquid and, meanwhile, facilitate particle rearrangement and thus assist densification. The CuSn powder showed an ellipsoidal morphology (Fig. 1(b)), while the CuP powder exhibited a generally spherical shape (Fig. 1(c)). Usually, such spherical or near-spherical particles in the powder system give higher coordination number and resultant higher loose packing density, thereby leading to a more efficient densification during sintering.

Fig. 2 shows the morphologies of the powder systems prepared at different dispersion conditions. When the components were mechanically mixed without the balls, the powder showed a significant agglomeration after dispersion (Fig. 2(a)). In this instance, the powder tends to affix close to the interior wall of the vessel because of the centrifugal effect, which makes the uniform dispersion of the powder cannot be easily obtained. When the powder was dispersed with the balls, the powder systems

<table>
<thead>
<tr>
<th>Powder</th>
<th>Size (μm)</th>
<th>Size distribution</th>
<th>Mean particle diameter (μm)</th>
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<tbody>
<tr>
<td>Cu</td>
<td>28–75</td>
<td>20%, &lt;38 μm; 80%, &lt;65 μm</td>
<td>54</td>
</tr>
<tr>
<td>CuSn</td>
<td>11–46</td>
<td>20%, &lt;22 μm; 80%, &lt;40 μm</td>
<td>28</td>
</tr>
<tr>
<td>CuP</td>
<td>5–24</td>
<td>20%, &lt;9 μm; 80%, &lt;20 μm</td>
<td>16</td>
</tr>
</tbody>
</table>

**Table 2**
Specifications of particle size of the starting powder components

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![Fig. 1. SEM images of the starting metal powder: (a) Cu powder; (b) CuSn powder; (c) CuP powder.](image-url)
as prepared generally exhibited less agglomeration due to the successive collisions between the particles and the dispersing media, and, meanwhile, the original shape of the particles was well retained (Fig. 2(b–d)). Thus, it is reasonable to term this dispersion approach as “ball mixing” rather than “ball milling”. Furthermore, Fig. 2(b–d) reveal a change of the powder with the mixing time. With a longer dispersing time, more fine particles were seen around the coarse ones, leading to an improvement in the dispersing uniformity and the resultant loose packing density of the powder.

3.2. Phase analysis

Fig. 3 shows the typical XRD patterns of No. 6 powder system and the corresponding laser sintered sample. The starting powder mixture mainly consisted of a matrix metal Cu and an intermetallic compound Cu₄₁Sn₁₁, while Cu₃P acted as the primary eutectic constituent phase of the pre-alloyed CuP (Fig. 3(a)). After sintering, the XRD data reveal that the Cu diffraction peaks slightly shifted to a low diffraction angle, leading to an increase in the lattice parameter for Cu. This is most likely that the larger Sn atoms with atomic radii of 0.158 nm substitute the Cu atoms with smaller radii of 0.128 nm in the crystal lattice, causing the crystal to expand. This analysis was further proved by detecting the formation of CuSn phase, a solid solution of Sn in Cu (Fig. 3(b)). Furthermore, a new phase Cu₃P was detected, but without the existence of oxide CuO or Cu₂O (Fig. 3(b)). This is because phosphorus acts as an in situ deoxidizer during sintering, protecting the Cu particle surface from oxidation and, thereby, permitting a sound solid–liquid wettability with minimal or no “balling” effect. In addition, Fig. 3(b) reveals that phosphorus still remained in the sintered sample as Cu₃P.
Despite a very small quantity of phosphorus (0.84 wt.%) in the original powder system. This suggests that only a fraction of this quantity of phosphorus reacts with oxygen due to the localized nature of the sintering in DMLS [5]. Excess phosphorus remains in certain regions as Cu₃P, since there is little or no oxygen with which it can react.

### 3.3. Characteristic microstructure

Fig. 4 shows the typical surface morphology of the laser sintered sample of No. 6 powder system. An excellent interparticle metallurgical bonding was achieved via a sintering neck. The EDX result reveals that the neck formed between Cu particles mainly consisted of Cu and Sn elements (composition: 90.56 wt. % Cu, 6.03 wt. % Sn, 1.62 wt. % P, and 1.79 wt. % O). This indicates that the mechanism of this process is liquid phase sintering, and the liquid formation is achieved by melting of CuSn but non-melting of the cores of Cu particles.

Fig. 5 shows the characteristic microstructure of the etched sample. It can be seen that a highly continuous network of dendrites was formed. Table 3 shows the chemical compositions of different positions in the laser sintered structure (measured by...
Table 3
Chemical compositions of different positions in the sintered structure (measured by EDX spot scan)

<table>
<thead>
<tr>
<th>Label</th>
<th>Position</th>
<th>Composition (wt. %)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Cu</td>
</tr>
<tr>
<td>A</td>
<td>Between dendrites</td>
<td>100.00</td>
</tr>
<tr>
<td>B</td>
<td>In dendrites</td>
<td>93.17</td>
</tr>
<tr>
<td>C</td>
<td>At grain boundaries</td>
<td>90.27</td>
</tr>
</tbody>
</table>

EDX spot scan. It is clear that such dendrites were CuSn solid solution, while the areas between dendrites were identified to be Cu-element-rich. This suggests that the binder CuSn melts and penetrates into the pores between the Cu particles which are bonded together by the liquid through the mechanism of liquid phase sintering. Furthermore, Table 3 reveals the segregation of phosphorus towards oxygen-rich areas. This is because phosphorus acts as an in situ sink for oxygen during sintering. Also, phosphor was found to be concentrating along grain boundaries (Table 3). This indicates that the solution of P in Cu is significantly suppressed, due to the low mutual solubility of P and Cu (less than 2 wt.% at 200°C [8]) as well as the extremely short laser sintering time.

3.4. Effect of powder dispersion conditions on densification and microstructure

Fig. 6 shows the characteristic microstructures of the laser sintered powder with variation of dispersion conditions. The densification and the attendant microstructural features such as...
Porosity, pore size and shape, and structural homogeneity are found to be depending on the change in the dispersion conditions. In the case of No. 1 powder system (Fig. 2(a)), the microstructure of the laser sintered sample was heterogeneous and consisted of the segregated and agglomerated Cu particles, showing a poor densification (Fig. 6(a)). Laser sintering of No. 2 powder system (Fig. 2(b)) led to an improved densification. However, the sintered structure remained heterogeneous due to a number of small pores existing in the matrix (Fig. 6(b)). Similar microstructure was obtained for laser sintering of No. 3 powder system (Fig. 2(c)), but the densification showed a pronounced increase (Fig. 6(c)). Interestingly, laser sintering of No. 4 powder system (Fig. 2(d)) resulted in the formation of a completely different microstructure consisting of highly continuous dendrites, showing a pretty homogenous structure with a higher attainable sintered density (Fig. 6(d)). Thus, it can be seen that a progressive transition from a highly heterogeneous and loose microstructure to a homogenous and dense one occurred with increasing the dispersing uniformity of the powder.

It is well known that the absorption rate of a powder bed significantly influences the material thermodynamic and kinetic characteristics during sintering [2,8,19]. In the case of multicomponent system, a homogenous powder mixture with less agglomeration of the binder is of critical importance in increasing the thermal absorption of the laser energy. This can further enhance the working temperature and the sintering kinetics which leads to higher sintered density. On the other hand, it has been reported that during the course of laser sintering, the localized mass transfer and material convection within the molten pool induced by the temperature and chemical gradients, as well as the subsequent rapid solidification process generally result in the formation of heterogeneous sintered structures [18,19]. However, our results, as shown in Fig. 6(d), suggest that a uniform dispersion of the powder can lead to favorable rheological properties of the molten liquid in conjunction with solid particles during sintering, and, thus, enhance the solid–liquid wettability and the subsequent particle rearrangement, thereby leading to a homogeneous microstructure.

3.5. Effect of binder content on densification and microstructure

Fig. 7 shows the typical microstructures on polished but non-etched sections of the laser sintered samples using different contents of the binder CuSn. It is clear that the microstructural characteristics, such as the amount of porosity, the size and shape

![Fig. 7. Optical images of the polished sections of the laser sintered samples using (a) No. 5, (b) No. 6, (c) No. 2, and (d) No. 7 powder systems at different contents of CuSn.](a) 400µm (b) 400µm (c) 400µm (d) 400µm
of pores, and the shape and coherence of the sintered agglomerations are associated with the change in the amount of CuSn. Fig. 8 shows the corresponding microstructures of the etched samples. Typically, the samples show dendritic structures in network shape. The EDX results reveal that such networks were Sn-rich constituents, indicating the melting and subsequent solidifying of CuSn powder during sintering. However, the microstructural features of the dendrites, e.g. homogeneity, continuity and density are also found to be depending on the variation of the content of CuSn. At a low CuSn content of 20 wt.%, narrow and discontinuous agglomerates were formed, which were separated by large and interconnected pore channels (Fig. 7(a)). Metallographic study at higher magnification shows that the microstructure was heterogeneous and consisted of a discontinuous network of thin dendrites (Fig. 8(a)). As the content of CuSn increased to 35 wt.%, some overlap between adjacent tracks were achieved and no transverse gaps were observed (Fig. 7(b)). In this instance, a highly continuous network of dendrites was formed (Fig. 8(b)). At a higher CuSn content of 50 wt.%, no individual scan tracks were found, instead a smooth and dense matrix was obtained (Fig. 7(c)). SEM analysis reveals the formation of an entirely continuous network of broad dendrites, showing a fully dense microstructure (Fig. 8(c)). However, when 65 wt. % CuSn was used, a number of irregular shaped pores were formed in the sintered structure (Fig. 7(d)), leading to a loose microstructure with a large amount of micro cracks (Fig. 8(d)).

Generally, direct laser sintering of the powder system as investigated involves complete melting of the CuSn powder but non-melting of the cores of the Cu particles. Therefore, the amount of liquid phase in the solid–liquid mixture influences the microstructures of the laser sintered parts by changing the thermodynamic and kinetic characteristics, such as solution,
viscosity, wetting, and particle rearrangement [5,6,8]. At a low content of CuSn, the liquid phase is only enough to bind the neighboring Cu particles, forming discontinuous agglomerates with large inter-track pores (Fig. 7(a)). Furthermore, the rearrangement force, which is induced by the capillary force of the liquid, is too low to rearrange all Cu particles, hence resulting in a poor densification with a heterogeneous microstructure (Fig. 8(a)). With increasing the content of CuSn, the surface tension and viscosity of the liquid decrease, and, accordingly, the flow of molten liquid becomes easier, leading to well-developed dendritic structures (Fig. 8(b and c)). Also, the rearrangement force of solid particles in the wetting liquid increases with the volume fraction of the liquid [8], thereby leading to a sufficient rearrangement of Cu particles and an improved densification of the powder (Fig. 7(b and c)). However, with large quantities of the liquid presented, the densification and the resulting microstructure become worse (Figs. 7(d) and 8(d)). This is because the excessive molten material with too low melt viscosity causes a significant “balling” effect [5]. Furthermore, the repulsion forces will arise between solid particles at a high volume fraction of liquid, thereby resulting in higher porosity [22].

3.6. Discussion

In laser sintering process, the laser energy is directly absorbed by the solid particles through both bulk coupling and powder coupling mechanisms [13,23]. The absorbed energy heats up the powder particles and, accordingly, increases the temperature of powder bed locally. It is well known that the pre-alloyed CuSn powder melts incongruently and has lower solubility and liquidus temperatures than the melting temperature of Cu. Therefore, liquid phase formation is achieved by melting the CuSn powder partially or fully during sintering. Partial or complete melting of the CuSn depends on the working temperature, which in turn depends on the amount of laser energy absorbed by the material. At the initial stage of sintering, liquid is presented at heterogeneous sites in the powder bed, typically grain boundaries and inter-particle regions. As the amount of energy absorbed by the powder under the laser beam increases, the local temperature increases, leading to a larger degree of melting. Under this condition, the powder layer loses rigidity and, hence, shrinks rapidly. When the temperature is raised above the liquidus temperature of the CuSn, complete melting of the binder occurs, and, subsequently, a so-called “sintering pool” containing both liquid and solid phases, as shown in Fig. 7, is expected to be formed. Because a Gaussian laser beam is used in the sintering, a large temperature gradient would be formed between the center and edge of the sintering pool, which gives rise to a surface tension gradient and resultant Marangoni convection [12]. The formation of Marangoni convection induces capillary forces for liquid flow and particle rearrangement, facilitating an efficient densification of solid particles with the wetting liquid.

The amount of the liquid presented in the sintering pool influences the densification and the resultant microstructure of the sintered parts by changing the thermokinetic and thermocapillary characteristics such as viscosity, wettability, and rheological properties [5,8]. Although there have been many equations proposed to model the viscosity of a solid–liquid mixture, \( \mu \), the following model proves most useful [5,24]:

\[
\mu = \mu_0 \left(1 - \frac{\varphi_l}{\varphi_m}\right)^{-2}
\]

where \( \mu_0 \) is the base viscosity that includes temperature terms, \( \varphi_l \) the volume fraction of liquid phase, and \( \varphi_m \) is a critical volume fraction of solids above which the mixture has essentially infinite viscosity. During laser sintering, particle bonding is controlled by the base viscosity, \( \mu_0 \), a strong temperature-dependent viscosity. This viscosity decreases with increasing the working temperature, thereby leading to better wetting characteristics and improved densification. However, the mixture viscosity \( \mu \) should be high enough to prevent “balling” phenomena [6,8]. This can be best obtained by controlling a right solid–liquid ratio [5]. Therefore, the combination of low \( \mu_0 \) and controlled \( \mu \) is of significance in achieving a sound sinterability.

In liquid phase sintering, the relative shrinkage of the powder bed can be estimated by the following equation [8]:

\[
\frac{\Delta L}{L_0} = \frac{k\gamma_{lv}t}{D\mu}
\]

where \( \gamma_{lv} \) is the liquid–vapor surface energy, \( t \) the sintering time, \( D \) the particle diameter, and \( k \) is a constant.

The sintered fractional density \( f_s \) for a powder bed starting at a fractional loose packing density \( f_p \) is given as follows [24]:

\[
f_s = f_p \left(1 - \frac{\Delta L}{L_0}\right)^{-3}
\]

Defining a non-dimensional parameter \( \alpha \) as

\[
\alpha = \frac{k\gamma_{lv}t}{D\mu_0}
\]

the final sintered fractional density can be expressed by Eq. (5) with a combination of the above equations [24]:

\[
f_s = f_p \left[1 - \alpha \left(1 - \frac{\varphi_l}{\varphi_m}\right)^2\right]^{-3}
\]

Eq. (5) shows that the densification of the laser sintered powder increases linearly with the initial loose packing density \( f_p \). Our results reveal that the density of loose powder is associated
with the powder characteristics and the corresponding dispersion conditions, and can be enhanced using the following approaches:

- Mixing coarse and fine powders with a broad particle size distribution (Table 2).
- Using spherical or near-spherical fine powders (Fig. 1).
- Homogenizing the powder mixture (Fig. 2).

Furthermore, it can be seen in Eq. (5) that the final sintered density increases with the volume fraction of liquid phase \( \varphi \) during laser sintering. The amount of liquid phase formation depends on the sintering temperature, which is related to the energy gain of the powder, and is mainly controlled by the characteristics of the binder in the mixture (the dispersing state and the weight fraction) if appropriate laser processing parameters are used. Our experimental results show that higher densification with homogeneous microstructures can be achieved by using:

- A uniformly dispersed powder with less agglomeration of the binder (Fig. 6).
- A proper content of the binder in the powder mixture (Figs. 7 and 8).

4. Conclusions

(1) A multi-component Cu-based metal powder consisting of Cu, CuSn, and CuP was developed for DMLS. The laser sintering of this powder system was carried out through the mechanism of liquid phase sintering.

(2) The powder characteristics such as particle shape, particle size and its distribution, and dispersion uniformity have a significant influence on the sintered density and the microstructural homogeneity.

(3) An optimization of the content of the binder in the powder mixture plays a key role in determining a higher densification of the laser sintered powder.

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