Numerical and experimental investigation of sintering deformation of brazing powder compacts

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Abstract
A modified sintering model was presented to analyze the deformation behaviors of brazing powder compact throughout the whole sintering process, both the thermal-mechanical plastic deformation and metallic alloying were implemented as sintering driving forces in the numerical simulation by the sintering model. Ag-Cu-Sn brazing powder compacts were prepared by electromagnetic compaction technique and sintered at different temperature, the simulated deformations were in reasonable agreement with the experimental deformations. Deformation analysis with different relative density was conducted by the sintering model to reveal the volume expansion mechanism and volume shrinkage mechanism throughout the whole sintering process, it was indicated that the sintering warpage or cracks are prominently related to relative density gradients, and the higher relative density of brazing powder compacts is beneficial to sintering densification. At last, the deformation behaviors of brazing powder compacts with three typical shapes were numerically predicted to provide guidelines for tool design and sintering process optimization.

Keywords: Sintering deformation, Powder compact, Brazing, Numerical simulation

1. Introduction

Due to the advantageous properties, such as environmental friendliness, greater corrosion resistance and preferable wettability (Kiebach et al., 2016, Fu et al., 2015), brazing is the most feasible and economical joining technique in structural and electronic applications. However, as a result of brittle compounds and the poor plastic workability evolved during the alloys smelting process, the brazing alloys are hard to be made into specific-shaped brazing sheet of minimum thickness in the conventional rolling process. Electromagnetic compaction is a high energy rate forming process with the advantages of high forming precision, greater compaction densification and less springback (Manoharan et al., 2013, Lee et al., 2004), and appears to be a preferable forming technology for preparing brazing sheet. During electromagnetic compaction for brazing powders, the brazing powders are firstly compacted into thin brazing sheet with designed dimensions and higher density (Hong et al., 2011, Lee et al., 2012), then the brazing sheets are sintered for alloys smelting or directly assembled on brazing section for brazing, the difficulties during conventional rolling process of brazing alloys can be successfully avoided.

The temperature evolution and densification behaviors have important influence on the powder compaction process (Yan et al., 2017, Lei et al., 2018). Moreover, sintering is an essential process for achieving necessary properties including higher mechanical strength, enhanced sintering densification, homogeneous density distribution and preferable alloying performance. But defects such as warpage, distortions or cracks are main concerns during sintering process as the brazing sheet undergoes dimensional changes (Uematsu, 2014). What’s more, it is costly and time-consuming for shape correction before the sintered sheets can match the brazing section within required tolerance. In the past decades, various mathematical sintering models have been proposed to further understand the deformation mechanism, and some were completed by numerical simulation to successfully predict the sintering densification,
deformation behaviors or residual stress. Riedel presented a constitutive equation for sintering mechanism, and the shrinkage or shear deformation were analyzed with grain boundary diffusion mechanism (Riedel, 1990). Shinagawa made a three-dimensional microscopic model for describing the deformation behaviors of viscous porous material under the action of sintering stress (Shinagawa, 1996). Gasik and Zhang (2000) predicted the dimensional shrinkage and sintering stress based on a thermal elasto-viscoplastic model, and the simulation results indicated that the maximum tensile stress arising at the cooling stage resulted in the surface crack in the cylinder specimen. Heterogeneity of relative density in green powder compacts is one of the major reasons for nonuniform sintering deformation or cracks (German, 2002, Mondal et al., 2016), the numerical modeling of material point method (Li et al., 2012) revealed the initiation and propagation mechanism of sintering cracks. A macro–micro modeling based on the homogenization theory was developed by Aizawa et al. (2002) to describe hot deformation and sintering behaviors of powder compacts at elevated temperature, and the phase transformation that accompanied with the significant volumetric change resulted in large strains or fracture. A numerical model based on a thermo-kinetic model was established by Mohsin et al. (2012), the densification process during sintering can be described using the thermo-physical data (density, thermal conductivity, specific heat as a function of temperature), and the results numerically simulated agreed well with the results experimentally observed in furnace sintering. However, most of the above sintering models are employed for sintering analysis of ceramic material or single–material powder compact, and principally focus on the volume shrinkage as a result of grain boundary diffusion. The brazing powder compact is a mixed powders of different metallic materials, and the sintering alloying is indispensable for required brazing performance. The prominent thermal-mechanical plastic deformation throughout the sintering process and the metallic alloying at elevated sintering temperature add more complex deformation behaviors and potential sintering failures, which are main concerns for brazing process design. A modified sintering model, that can integrate both thermal-mechanical plastic kinetic and the metallic alloying, is necessary to precisely predict the sintering deformation behaviors and potential failures throughout the whole sintering process.

In this study, a sintering model of brazing powder compact was presented to analyze the deformation behaviors throughout the whole sintering process, the residual stress relaxing at lower temperature and atom diffusion were considered as the two main driving forces for sintering deformation. Sintering tests of Ag-Cu-Sn brazing powder compacts were completed to validate the sintering model. At last, deformation analysis with different relative density was conducted by this sintering model to reveal the volume expansion mechanism and volume shrinkage mechanism throughout the whole sintering process, also the deformation behaviors of brazing powder compacts with three typical shapes were numerically predicted to provide guidelines for tool design and sintering process optimization.

2. Sintering model

2.1 Yield function

Brazing powder compact is regarded as a compressible material, and its deformation depends on both deviatoric stress and hydrostatic stress. The yield function is given as,

\[
AJ_2' + BJ_1^2 = Y_R^2 = \alpha Y_0^2
\]

Where \(J_1\) is the first stress invariant and \(J_1 = \sigma_{kk} = 3\sigma_m\), \(\sigma_m\) is the hydrostatic stress, \(J_2\) is the second deviatoric stress invariant and \(J_2' = \frac{1}{2}\sigma_{yy}'\sigma_{yy}'\), \(\sigma_{yy}'\) is deviatoric stress, \(Y_R\) and \(Y_0\) are the yield stresses of the base material and porous material, respectively. \(\alpha\), \(A\) and \(B\) are relative density functions and defined by series of physical tests.

The deformation of powder compact during sintering can be regarded as a result of sintering driving force within the compact, which functions as hydrostatic stress (Svoboda et al., 1994). Then the yield function \(F\) during sintering can be expressed as,

\[
F = AJ_2' + B\left(J_1 - 3\sigma_s\right)^2 = Y_R^2 = \alpha Y_0^2
\]

Where \(\sigma_s\) is the sintering driving force during sintering process. The yield function considering the sintering
stress can be described as shown in Fig.1. In condition of higher sintering temperature, the yield stress decreased with increasing strain, then the radius of the ellipsoidal yield curve decreased when the sintering temperature of powder compact increases.

At high working temperatures, the yield stress reduces while the strain increases. Accordingly, the radius of the ellipsoidal yield curve decreases when the temperature of the porous body increases as illustrated.

![Fig.1 Yield curve of powder compact considering sintering stress (the sintering temperature is represented by $T$)](image)

2.2 Constitutive equation

The viscous plastic strain rate of porous material is given by,

$$\dot{\varepsilon}_y = \dot{\lambda} F/\partial \sigma_y = \dot{\lambda} \partial(A \sigma_{ij}' \sigma_{ij}' /2 + B(\sigma_{kk} - 3\sigma_s)^2)/\partial \sigma_y$$

(3)

Where $\sigma_{ij}$ can be divided into deviatoric stress and volumetric stress (Jeong et al., 2012). Then by partial differentiation of $A \sigma_{ij}' \sigma_{ij}' /2$, it can deduce as,

$$\partial(A \sigma_{ij}' \sigma_{ij}' /2)/\partial \sigma_{pq} = A \sigma_{ij}'$$

(4)

By partial differentiation of $B(\sigma_{kk} - 3\sigma_s)^2$, it can deduce as,

$$\partial(B(\sigma_{kk} - 3\sigma_s)^2)/\partial \sigma_{pq} = 2B(\sigma_{kk} - 3\sigma_s)\delta_{ij}$$

(5)

Then the viscous plastic strain rate is deduced as,

$$\dot{\varepsilon}_y = 2\dot{\lambda}(A \sigma_{ij}' /2 + B(\sigma_{kk} - 3\sigma_s)\delta_{ij})$$

(6)

Where $\dot{\lambda}$ is a proportional factor and $\dot{\lambda} = \tilde{\varepsilon}_R /2\dot{\sigma}_R - \dot{\varepsilon}_{kk} \sigma_s /2\dot{\sigma}_R^2$, where $\dot{\sigma}_R$ is effective stress and $\tilde{\varepsilon}_R$ is effective strain rate, and are given as follows,

$$\dot{\sigma}_R^2 = A \sigma_{ij}' \sigma_{ij}' /2 + B(\sigma_{kk} - 3\sigma_s)^2$$

(7)

$$\tilde{\varepsilon}_R = (2\dot{\varepsilon}_{ij}' \dot{\varepsilon}_{ij}' /A + \dot{\varepsilon}_{kk} \dot{\varepsilon}_{kk}/9B)^{1/5} + \sigma_s \dot{\varepsilon}_{kk}/\dot{\sigma}_R$$

(8)

2.3 Sintering driving force and viscosity

The sintering mechanism of brazing powder compact is hypercomplex, and the sintering driving force is determined by relative density, surface energy, powder size, grain growth, boundary diffusion and others (Gasik and Zhang, 2000, Reiterer and Ewsuk, 2009). In the sintering history, the residual stress existing within powder compact will be firstly relaxed at lower sintering temperature, and atom diffusion plays as main sintering driving force to reduce the surface energy when the sintering temperature is increased. In this study, the residual stress relaxing is regarded as a part of sintering driving force at lower sintering temperature to evaluate the sintering mechanism throughout the whole
sintering process. The sintering driving force is expressed as,

$$\sigma_s = \sigma_a - \sigma_r$$  \hspace{1cm} (9)

Where \(\sigma_a\) is the sintering driving force due to atom diffusion, and \(\sigma_r\) is the equivalent tension stress for residual stress relaxing. The phenomenological model presented by Olevsky (1998), which is in consistence with rheological sintering theory completed by Skorohod, is widely used for numerical studies of metallic or ceramic sintering mechanism (Sahli et al., 2015, Skrokhod, 1972), and is expressed as,

$$\sigma_a = C\gamma R^2 / r_0$$  \hspace{1cm} (10)

Where \(C\) is material constant, and \(C = 3\) for spherical powder particles (Skrokhod, 1972), \(\gamma\) is surface energy, \(R\) is relative density of powder compact, \(r_0\) is radius of spherical powder particles.

The yield stress of metal material is decreasing with the increase of temperature, the residual stress within powder compact may be gradually relaxed in form of plastic deformatons of powder particles. The residual stress relaxing functions as equivalent tension stress to the volume expansion mechanism at lower sintering temperature (Ding, 2001). The equivalent tension stress for residual stress relaxing is expressed as,

$$\sigma_r = \begin{cases} aR_0(T_f - T) & T_s < T < T_f \\ 0 & T \geq T_f \end{cases}$$  \hspace{1cm} (11)

Where \(a, b\) are adjustable parameters that are related to material properties, compaction process and heating process, \(R_0\) is the initial relative density of powder compact before sintering, \(T_s, T_f\) are the starting temperature, finish temperature of residual stress relaxing, respectively. All the above parameters are defined by series of sintering tests. \(T\) is absolute heating temperature.

The powder compact consists of base material and adjacent pores with random isotropic distribution. When the grain boundary diffusion is the predominant mechanism for sintering deformation, the viscosity can be modeled using the Coble’s Creep Model (Coble, 1963),

$$\eta(T) = K G^3 R^2 T e^{Q/R T}$$  \hspace{1cm} (12)

Where \(K\) is adjustable parameter that is related to atomic volume, coefficient of grain boundary diffusion and others, \(G\) is grain size, \(Q\) is effective activation energy for grain boundary diffusion, \(R_g\) is gas constant.

And it is deduced as follows,

$$A = (1 + v_{vp})/(\dot{\lambda} \eta(T))$$  \hspace{1cm} (13)

$$B = (1 - 2v_{vp})/(6\dot{\lambda} \eta(T))$$  \hspace{1cm} (14)

Where \(v_{vp}\) is viscous Poisson’s ratio (Bordi and Scherer, 1988), and \(v_{vp} = 0.5 \sqrt{R/(3-2R)}\).

2.4 Formulation of relative density dependent discretization

The equilibrium equation of porous material is given as,

$$\int_{\Omega} \sigma_{\mu} \delta \varepsilon_{\mu} dV - \int_{S_r} F_{\mu} \delta u_{\mu} dS = 0$$  \hspace{1cm} (15)

Where \(u\) is elemental velocity field, and \(u = N^T \nu\), where \(\nu\) is velocity vector of nodal-point value, and \(N\) is shape function matrix.
The effective strain rate of porous material is related to both external force and thermal expansion (functioning as $\dot{\varepsilon}_{R_0}$, and $\dot{\varepsilon}_{R_0} = \dot{\varepsilon}_R + \alpha \dot{T}$, where $\dot{\varepsilon}_R$ is related to external force, and $\alpha$ is thermal expansion coefficient) and sintering driving force (functioning as $\dot{\varepsilon}_{R_s}$) (Jeong et al., 2012), which is given by,

$$\dot{\varepsilon}_R = \dot{\varepsilon}_{R_0} + \dot{\varepsilon}_{R_s}$$

(16)

Then the total variation of the effective strain rate is deduced as follow,

$$\delta \dot{\varepsilon}_R = \delta \dot{\varepsilon}_{R_0} + \delta \dot{\varepsilon}_{R_s} = \delta \dot{\varepsilon}_T B^T DB \dot{v} + \dot{\varepsilon}_R + \sigma^T B \delta \dot{v} / \dot{\varepsilon}_R$$

(17)

Where $B$ is strain rate matrix, $D$ is elastic matrix, and $C^T = c^T B$, where $c^T = (1 1 1 0)$ for two dimensional deformation or axis-symmetrical deformation, and $c^T = (1 1 1 0 0 0)$ for three dimensional deformation.

From Equation (15) and Equation (17), it is deduced as follow,

$$\int \frac{\dot{\varepsilon}_R B^T DB \dot{v} + \int \sigma^T B \delta \dot{v} - \int_{S_f} F_I N dS}{\dot{\varepsilon}_R} \delta \dot{v} = 0$$

(18)

3. Sintering test

The brazing powder compact is made of 60Ag-31Cu-9Sn (wt.%) powders, the powders were prepared by gas atomization process and the average size is about 43µm. The relative density of powder compact is determined by discharging voltage and discharging capacitance during electromagnetic compaction (Psyk et al., 2011). As shown in Fig.2, the powder compacts were placed in sintering boat and burying sintered in a vacuum environment. The heating rate is 10K/min, and cooled in the furnace after 20 minutes sintering preservation.

![Sintering layout of powder compact](image)

4. Result and discussion

4.1 Simulation result and analysis

A numerical simulation by the sintering model was completed, and the input parameters are listed in Table1. The brazing material is assumed to be linear viscous, and the thermal expansion coefficient is treated as a constant due to its small variation when the relative density is over 0.8, as shown in Fig.3.

| Table 1 Input parameters of sintering model |
|--------------------------------------------|
| $K$ | $G$ | $Q$ | $R_g$ | $C$ | $\gamma$ | $r_o$ | $a$ | $b$ | $T_s$ | $T_f$ |
| Pa·s/(m³·K) | µm | J/mol | J/(mol·K) | J/m² | µm | | | | | |
| 7.3×10⁻¹⁵ | 3.67 | 300371 | 8.314 | 3 | 1.317 | 43 | 0.0172 | 0.732 | 353 | 613 |

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Circular brazing powder compacts with 0.5mm thickness, 16mm diameter and 0.93 initial relative density were sintered at different temperature in a vacuum environment, and the finite element simulations were conducted by the sintering model to compare with the radial deformation from sintering experiments. As shown in Fig.4, in the early stage of sintering process when the sintering temperature is lower than 300°C, the simulated deformation is a little lower than experimental deformations. But the simulated deformation is consistently larger than experimental deformations when the sintering temperature is higher than 300°C. According to equation (10), the sintering driving force of atom diffusion is hypothesized to be independent of sintering temperature, then the sintering alloying is over-predicted at lower sintering temperature and underestimated at higher sintering temperature than 300°C. On the whole, the simulated deformations have reasonable agreement with experimental deformations.

The sintering deformation consists of volume expansion mechanism and volume shrinkage mechanism. The volume expansion occurs when the sintering temperature is lower than 400°C, which can be explained by residual stress relaxing and thermal expansion. The volume shrinkage gradually becomes the dominant when the sintering temperature is higher than 400°C, which is explained by the prominent sintering driving force of atom diffusion. The sintering alloying of metallic powder materials can fundamentally contribute to the sintering densification when the sintering temperature is higher than 600°C. Without considering the thermal expansion in the sintering model, the simulated deformation is consistently smaller than the experimental deformations throughout the whole sintering process, and makes faster volume shrinkage at elevated temperature over 600°C, which is due to the greater sintering driving force of atom diffusion that is related to higher relative density caused by smaller simulated volume expansion at lower temperature. The residual stress relaxing of metallic powder compact is the dominating factor to volume expansion in the early stage of sintering process. The sintering force of atom diffusion is the sole contributor to volume shrinkage throughout the sintering process, which plays the dominating role for sintering densification of brazing powder compacts. It can be concluded from the above analysis that the residual stress relaxing, thermal expansion and atom diffusion are indispensable factors to precisely evaluate the sintering deformation behaviors throughout the whole sintering process.
The simulated radial deformation at different sintering temperature is shown in Fig.5. It is shown that the brazing powder compact goes through volume expansion at lower temperature and volume shrinkage at elevated temperature, and the radial deformation keeps in a concentric annular distribution. The maximum radial deformation occurs at the outer edge of sintered compact, while the zero deformation at centerpoint of sintered compact. The positive values of radial deformation represent the radial expansion of sintered compact, and the negative values represent the radial shrinkage. The circular curves of black color describe the original outlines of powder compact before sintering.

4.2 Deformation analysis with different relative density

As shown in Fig.6, as a result of more residual stress relaxing and larger thermal expansion during the early sintering stage when the sintering temperature is lower than 400°C, the volume expansion of brazing powder compacts with higher relative density represents a greater increase than that of lower relative density. The powder compact with relative density of 0.93 makes the largest volume expansion, and the powder compact with relative density of 0.85 makes the smallest volume expansion. When the sintering temperature is higher than 400°C, the volume shrinkage of brazing powder compacts is strongly driven by the greater sintering driving force of atom diffusion, so the volume shrinkage of brazing powder compacts with higher relative density represents a faster decrease than that of lower relative density. The smaller pores of brazing powder compacts with higher relative density can be more easily eliminated by atom diffusion. In contrast, the larger pores of brazing powder compacts with lower relative density may result in less volume shrinkage at elevated temperature, or even lead to volume expansion at finishing time of sintering if the value of volume shrinkage is lower than the value of volume expansion. It can be concluded that higher relative density of brazing powder compacts is beneficial to sintering densification, especially for the metallic powder compacts with prominent sintering alloying at elevated temperature.

Fig.5 Simulated radial deformation at different sintering temperature (a is at 200°C, b is at 400°C, c is at 600°C, d is at 750°C, and the deformation scaling factor is 2)

Fig.6 Deformation curve with different relative densities
The axial density gradients evolved during powder compaction are related to the greater die wall/powder friction, higher ratio of height to diameter of powder compacts, or restricted particle flow under small compaction pressure. The relative density gradient is the dominating factor to sintering warpage or cracks. As shown in Fig.7 (a), a simulation model with axial density gradient was made to study the sintering deformation behaviors, the radius of the circular powder compact is 16mm, the thickness is 0.5mm, and the thickness is equally divided in to three parts. The relative density of the brazing powder compact decreases from top to the bottom, the relative density of top part, middle part and bottom part are defined at 0.95, 0.94 and 0.93, respectively. After 700°C sintering, the top part of the powder compact makes the greatest volume shrinkage, while the smallest volume shrinkage in the bottom part, then deformation warpage in the direction towards the top part can be found at the external edge of sintered compact. The residual tensile stress within the sintered compact body, which is evolved by the sintering warpage, is the proximate cause of sintering cracks as shown in Fig.7 (b).

4.3 Deformation analysis with different shape

The brazing powder compacts are usually designed in specific shape to match the brazing section within required tolerance. Due to the more or less inhomogeneous density distribution or complex geometry, the brazing powder compacts may undergo shape distortions or cracks during sintering process. In order to reduce the shape corrections by hard machining or other post-processing techniques, the sintering deformation behaviors should be precisely predicted by the sintering model, and corresponding compensation designs can be made during tool design stage to meet the tolerance requirements or avoid potential cracks. Three typical shapes were selected in this numerical deformation analysis with different shape, which are ring shape, L shape and rectangular shape. The relative density of the three shapes is 0.95, the constraint boundary is applied on the shape center for ring shape and rectangular shape, and on the internal corner for L shape. The simulated deformations of three shapes at 700°C are shown in Fig.8. The radial deformation of ring shape is in a concentric annular distribution, the maximum radial deformation occurs at the outer edge and the minimum at the inside edge. L shape makes an uniform volume shrinkage, the outlines still keep in straight and the right angles are unchanged. The shrinkage in length direction of rectangular shape is larger than that of
width direction, and the zero deformation exists at the geometrical center.

Fig.8 Deformation of sintered brazing powder compact with different shape at 700°C (a is ring shape, b is L shape, c is rectangular shape, and the deformation scaling factor is 10)

5. Conclusions

A modified sintering model was presented to analyze the deformation behaviors of brazing powder compact throughout the whole sintering process, the thermal-mechanical plastic deformation and metallic alloying are implemented as two main sintering driving forces in the sintering model. Sintering tests of Ag-Cu-Sn brazing powder compacts were completed, and the simulated deformations were in reasonable agreement with the experimental deformations. Deformation analysis with different relative density and different shape were numerically conducted by the sintering model. The conclusions can be drawn from the experimental and simulated results as following:

1) The powder compact of mixed metallic materials represents a prominent thermal-mechanical plastic deformation and significant metallic alloying during sintering process, the residual stress relaxing, thermal expansion and atom diffusion are indispensable factors to precisely evaluate the sintering deformation behaviors throughout the whole sintering process.

2) The sintering deformation of brazing powder compact consists of volume expansion mechanism and volume shrinkage mechanism. The volume expansion at lower temperature can be explained by residual stress relaxing and thermal expansion, and the volume shrinkage at elevated temperature is mainly determined by the prominent sintering driving force of atom diffusion during metallic alloying.

3) In condition of prominent sintering alloying at elevated temperature, the higher relative density of brazing powder compacts is beneficial to sintering densification. The relative density gradient within the brazing powder compact is the dominating factor to sintering warpage or cracks.

4) The shape is another important issue to sintering deformation of brazing powder compact. Based on the precise prediction of sintering deformation behaviors, corresponding compensation designs can be made during tool design stage to eliminate the potential sintering defects and guarantee tolerance requirements in brazing process.

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