Analysis and Design of a Press-and-Sinter Process for Fabrication of Precise Tungsten Carbide Cutting Tools

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ABSTRACT
Distortion during sintering has been a critical problem in the fabrication of hard materials such as tungsten carbide by the conventional press and sinter process. Until now, cures for the distortion problem have included changes in the polymer additives, tool motion, and various sintering tricks. This paper shows the sources of distortion can be modeled via computer simulation. As a consequence, we back-calculate the die shape to obtain precise final shapes. In this study, the simulation results by PMsolver (CAE design associated with the conventional P/M process) are verified. The compaction schedule is designed to obtain as uniform a green density distribution as possible and the effect of loading schedule on distortion during sintering are compared to experimental results.

INTRODUCTION
Within the context of the conventional P/M process, diverse methodologies have been developed to improve product quality. Net-shaping enables a low unit cost. With the development and expansion of information technology (IT) industry, the needs for smaller and more complex components are increasing. Since powder injection molding (PIM) has strength in those areas, it now holds a leading role in high-volume, complex-shape, high-performance manufacturing [1]. Nonetheless, the conventional P/M process, consisting of die compaction and sintering, is preferred for relatively simple shapes because of lower unit costs [2].

One of the main drawbacks of die compaction is heterogeneity in green density distribution which leads to warpage and even cracking during ejection. The heterogeneity in green density distribution after compaction gives rise to distortion during sintering process, since sintering shrinkage amplifies density gradients into sintered dimension gradients. This problem is especially severe with hard materials that resist plastic deformation in compaction. In fact, cutting tool manufacturers report over 30% of their production cost is associated with grinding the distorted part after sintering. To reduce this heterogeneity,
researchers have studied on the use of new lubricants, but the effect of lubricants is very confined since the heterogeneity is due to several sources - friction between the powder and die wall as well as heterogeneous normal stress acting on the powder compact from die. A remedy for distortion may be to modify die shape in compaction by considering the distorted amount during sintering. Sometimes this problem is termed the inverse problem and it requires a nonexistent anti-sintering algorithm. However, the modification of die or punch shapes is not only expensive and time-consuming but still considered a pioneering project in P/M industry.

In this study, the design of the compaction tool loading schedule, that is the movement of punches and dies with time during compaction, is studied as an alternative approach to minimized distortion. Though the heterogeneity after die compaction is inevitable, the amount of heterogeneity can be improved by selecting a proper loading schedule. With new computer numerically controlled presses that allow independent programming of all motions, this solution approach is reasonable. Since the change in loading does involve additional tool expense, it is a practical remedy for the distortion problem only if the density is homogeneous [3]. It is important to see the density distribution inside powder compact after die compaction for the design of loading schedule so as to obtain a uniform density distribution as possible. The efficient way for this purpose is to use finite element analysis. However, there is no exclusive CAE software available for the conventional P/M process and researchers have been relied on general purposed commercial CAE software [4]. The general purposed CAE software has convergence problem in simulation of P/M process because the formulations are incongruent for compressible P/M process. Especially, the convergence problem is serious in three-dimensional analysis of the P/M process and some researchers have used explicit CAE software in 3-D analysis [5]. However, explicit time integration schemes have accuracy problems. Therefore, we developed an exclusive CAE software for die compaction (PMsolver/Compaction-3D) based on the implicit time integration.

Using PMsolver, the effect of a selected loading schedule on green density distribution after compaction is used to guide the selection of an optimal loading schedule for a WC-Co hard material. First of all, the material parameters to precisely predict densification behavior during die compaction are found based on Shima and Oyane’s model [6]. Then, PMsolver is verified by comparing the density distribution predicted by PMsolver with experimental result and with parallel calculations using ABAQUS/Explicit [7]. Then, the optimal loading schedule is designed through iterations with a simplified 2-D axisymmetric geometry. Finally, the green density distribution (a precursor to distortion in sintering) is compared between the established loading schedule and our newly identified optimal loading schedule. Distortion is determined using a finite element simulation of sintering with inputs of the green density distributions and geometry predicted after die compaction.

**MODELING OF DIE COMPACTION**

**Constitutive model**

The constitutive model that predicts the densification behavior of a powder during die compaction is prerequisite for this numerical analysis. Many researchers have studied various constitutive models. The general trend is to consider the difference in the behavior against compression and tension such as contained in the Cam-Clay and Drucker-Prager models. However, these constitutive models improperly treat the tensile response and potentially overestimate the resistance to tensile stresses, resulting in an inability to properly predict green crack generation. In addition, these constitutive models upset convergence in the finite element analysis, since the yield surface of these constitutive models is not smooth near the intersection point of the failure line and Cap surface. Thus, we elected to use a more conventional constitutive model proposed by Shima and Oyane based on uniaxial compression tests:
\[ \Phi = \left( \frac{q}{\sigma_m} \right)^2 + 6.20(1-D)^{1.028} \left( \frac{p}{\sigma_m} \right)^2 - D^5 \]  

(1)

Where, \( q \) and \( p \) are the effective stress and hydrostatic pressure, \( D \) is the relative density, and \( \sigma_m \) is the flow stress of the matrix material. Many researchers have used Eq. (1) to analyze the compaction process with various powder materials. Recently, Eq. (1) has been successfully applied to die compaction process with stainless steel powder [4]. However, Eq. (1) was derived from the uniaxial compression and tension experiments with copper powder from the following generalized yield criteria:

\[ \Phi = \left( \frac{q}{\sigma_m} \right)^2 + \alpha (1-D)^{\gamma} \left( \frac{p}{\sigma_m} \right)^2 - D^m \]  

(2)

where \( \alpha \), \( \gamma \) and \( m \) are the material parameters. Therefore, Eq. (1) is the yield functions for only copper powder and new material parameters in Eq. (2) have to be determined for other powder materials.

**Determination of material parameters**

In addition to the material parameters for yield criteria, the flow stress of matrix material \( \sigma_m \) and friction coefficient \( \mu \) need to be measured prior to numerical analysis. The conventional procedure is to measure these parameters is complicated: Material parameters \( \alpha \), \( \gamma \) and \( m \), for the yield criteria in Eq. (2) are obtained using a triaxial test, although Shima and Oyane demonstrated alternative uniaxial compression and tension tests. Then, to measure the flow stress of the matrix material \( \sigma_m \), a uniaxial compression test is used with a bulk sample prepared by hot isostatic pressing. However, hot isostatic pressing is time consuming. Even more of a problem, the flow stress during hot isostatic pressing is different from that of powders due to the microstructural evolution during hot isostatic pressing. Finally, for a hard material there is substantial polymer binder used in die compaction that is missing in the hot isostatic pressing experiments. Thus, since the friction coefficient \( \mu \) depends on the particle size, hardness, roughness of tool, amount of lubricant and so on, tests using hydrostatic compression via hot isostatic pressing are rejected. Many efforts have been tried to measure the friction coefficient but it is still an important research issue. Kwon et al. [4] reports a novel approach that uses the ejection force with an applied pressure to measure the friction coefficient.

The conventional procedure explained above is hard to use in an industrial setting, since it needs several expensive tests and access to special equipment. Further, basic data generation can be very time consuming. To simplify the procedure to measure the material parameters, \( \alpha \) and \( \gamma \) are assumed to be invariant with powders, where the values found by Shima and Oyane are used as follows.

\[ \alpha = 6.20, \gamma = 1.028 \]  

(3)

In this study, the simplified procedure proposed by Kwon et al. [3] is used by assuming that \( \alpha \) and \( \gamma \) are invariant to powders.

Then, the matrix material is assumed to be work-hardening in form of following equation:

\[ \sigma_m = a + b \bar{e}_m^n \]  

(4)

where, \( a \), \( b \) and \( n \) are the material parameters and \( \bar{e}_m \) is the effective strain of matrix material.
This simplified procedure needs only a series of die compaction tests by single action pressing instead of the complications of triaxial tests, hot isostatic pressing, and uniaxial compression. To find material parameters $m, a, b$ and $n$, cylindrical die compaction tests are carried out. For this procedure, it is very important to minimize the friction effect as much as possible. Two treatments are used for this purpose. First, the movement of punch should is minimized by reducing the amount powders. Second, the die wall should be well lubricated using a lubricant coating on the die wall surface. Then, the relative density versus pressure data are fit to extract $m, a, b$ and $n$ based on the least square method. Then the friction effect is increased to measure the friction coefficient $\mu$. For this procedure, the amount of powders is increased and like traditional compaction no die wall lubricant is used. By comparing the finite element simulation results using a Coulomb friction model with the experimental data, an appropriate frictional coefficient is determined.

In this study, a standard cemented tungsten carbide powder, P25, was used. The physical property and chemical composition are shown in Table I. Figure 1 shows a scanning electron micrograph of the powder. For die compaction, 4 g and 10 g of powders were poured into a cylindrical die 11.28 mm in diameter and tapped. The smaller mass, is used to measure the material parameters, $m, a, b$ and $n$ and the larger mass is used to measure the friction coefficient. Compaction loads ranged up to 400 MPa.

<table>
<thead>
<tr>
<th>Chemical composition [mass%]</th>
<th>Average particle size [(\mu m)]</th>
</tr>
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<tbody>
<tr>
<td>WC</td>
<td>60 ~ 83</td>
</tr>
<tr>
<td>TiC</td>
<td>5 ~ 10</td>
</tr>
<tr>
<td>TaC</td>
<td>5 ~ 15</td>
</tr>
<tr>
<td>C</td>
<td>0 ~ 15</td>
</tr>
<tr>
<td>Co</td>
<td>6 ~ 9</td>
</tr>
<tr>
<td>Binder</td>
<td>2 ~ 3</td>
</tr>
</tbody>
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Figure 1. Scanning electron micrograph of cemented tungsten carbide powder, P25
Figure 2 plots the relative green density against applied pressure from both the experiment and model. The fitted material parameters of cemented tungsten carbide powder are as follows:

\[ m = 20.8, \sigma_m = 5100 + 4310 \tau_m^{0.16}, \mu = 0.1 \]  

(5)

Density distribution in the powder compact after die compaction is generated by measuring the Rockwell superficial hardness, since hardness is mainly the function of relative density. Figure 3 shows the variation of relative density with Rockwell hardness can be represented by the following equations:

\[ D = 0.63829 + 1.6712 \times 10^{-3} \cdot (HR15T) + (-5.4404 \times 10^{-7}) \cdot (HR15T)^2 \]  

(6)

Figure 2. Variation of relative green density with uniaxial compaction pressure for P25 powder.

Figure 3. Variation of relative green density with Rockwell hardness (HRT15) for P25 powder.
VERIFICATION OF FINITE ELEMENT SIMULATION

According to the time integration scheme, finite element formulations can be classified as implicit code and explicit code. In general, explicit code is more efficient than implicit code in terms of computing time and convergence, since an explicit code does not need to solve matrix equation. However, an explicit code may have problems with the solution accuracy, especially when applied to relatively slow processes. Therefore, explicit code is generally used for dynamic and impact analysis, but die compaction is not included in this category. Up to now, ABAQUS/Standard has been commonly selected for the analysis of die compaction, since it supports user subroutine UMAT. However, ABAQUS/Standard can have convergence problems in simulating die compaction process. This is especially true for 3-D analysis where convergence problems seem inevitable. Therefore, ABAQUS/explicit code is being used for the analysis of the 3-D process regardless of the inaccuracy of the solution without verification.

We developed PMsolver/Compaction-3D to obtain more accurate solutions and to facilitate the use of CAE software for the conventional P/M process. PMsolver/Compaction-3D is die compaction oriented CAE software, which is based on implicit time integration and a rigid viscoplastic algorithm. The results from PMsolver/Compaction-3D were verified using 3D cylinder compaction. Figure 4 shows the initial mesh system and boundary conditions. A total of 7,085 tetrahedral elements were used for the finite element analysis with the P25 powder parameters given in Eq. (5).

![Finite element meshes and boundary conditions for the cylindrical compact](image)

Figure 4. Finite element meshes and boundary conditions for the cylindrical compact

A comparison of green density distribution in the cylinder cross section showed quite a difference between approaches as is evident in Figure 5. The experimental relative green density distribution data were generated from the hardness trials and hardness-density correlation. From the viewpoint of symmetry of density distribution and quantitative comparison of relative density distribution with experimental data, the result of PMsolver/Compaction-3D was superior to that of ABAQUS/explicit. In addition, the flexibility of an implicit code in determining time step size can compensate the weakness of implicit code in terms of computing time.
The finite element analysis was applied to a more practical example, the so-called VBMT shape cemented carbide (WC-Co) insert. Figure 6 shows the final shape of VBMT and Figure 7 shows the initial mesh systems with tetrahedral elements, where the initial relative green density of the powder compact was 0.42. Based on the material parameters expressed in Eqs. (3) and (5), the deformation behavior of the powder compact was simulated for the VBMT shape. Compaction tool sets for producing the VBMT shape consist of an upper punch, lower punch, and die. During forming the upper punch moved down at 150 mm/s, the lower punch moved up at 100 mm/s, and the die remained stationary.

Figure 6. Final compressed shape of the VBMT cutting insert.
Figure 7. Finite element mesh for the cemented carbide powder compact.

Figure 8 shows final relative density distribution obtained. The difference in density distribution after die compaction is directly related to the difference in densification amount during sintering, which results in distortion during sintering. Therefore, to minimize distortion of the sintered shape it is important to obtain a pressed compact with a uniform green density distribution. Along the edges of the top surface, density was locally quite low as compared with other region, but this local difference does not heavily affect global sintering distortion such as bending. Instead, the difference of density distribution along the longer axis and along the shorter axis has the largest effect on sintering distortion.

Figure 9 compares the relative green density distribution on the cross sectional area between predicted value by the finite element simulation and experimentally measured value. The results showed locally slight differences, but the overall trend in relative density distribution shows good agreement. The difference is thought to be mainly due to the experimental error in measuring Rockwell hardness.

Figure 8. Relative green density distribution predicted after die compaction.
Figure 9. Comparison of relative green density distribution on the cross section from experiment and finite element simulation.

DESIGN OF COMPACTION LOADING SCHEDULE

To minimize the green density variation, the optimization technique shown in Figure 10 was used to design the loading schedule. The optimization technique is a derivative-based approach, which has been applied to various metal-forming processes. The application of optimization technique for die compaction worked well to find the loading schedule that might be applied in computer-controlled compaction press [3]. A mesh was generated with initial guesses on the operating variables. Then, using the given process conditions and mesh system, finite element simulation was carried out. These results were used to search for parameter change directions and step sizes to improve the product. The searching direction depends on the design sensitivity and the searching direction depends on polynomial curve fitting. On an iterative basis the design variables were updated. These cycles are repeated until the convergence criterion was satisfied. The object function is the deviation of relative green density distribution after die compaction as shown in Eq. (6).

\[ \Phi = \int_{\Omega_f} (\rho - \bar{\rho})^2 \, d\Omega \]  \hspace{1cm} (6)

where \( \Omega_f \) means the analysis domain in final state and \( \bar{\rho} \), average relative density, is calculated below.

\[ \bar{\rho} = \frac{\int_{\Omega_f} \rho \, d\Omega}{\int_{\Omega_f} d\Omega} \]  \hspace{1cm} (7)
When compared with the previous approaches and finite element applications, our current process is relatively simple. Part of that simplicity arises since only one upper punch and one lower punch movement is considered as design variables. Core rods, steps, and other motions might complicate the analysis. Since the component has a tapered hole, the motion of the other punch should be determined so as to conserve the initial powder amount. Considering calculation time and difficulty with 3D mesh generation, the 3D shape was simplified into a 2D axisymmetric shape as shown in Figure 11. Figure 12 shows the variation of object function with optimization iteration.

Figure 10. Flow chart of optimization scheme.
Figure 11. Simplified 2D axisymmetric model near the tapered hole in the VBMT shape.

Figure 12. Variation of object function with optimization iteration.

The 3D finite element simulation created using PMsolver/Compaction-3D was carried out with this newly generated mesh system according to the optimal loading schedule. Figure 13 shows the relative density distribution after die compaction. A comparison of Figures 8 and 13 shows the effect of loading schedule on the relative green density distribution. When an optimal loading schedule is selected, the difference of
min/max values is smaller and the relative green density distribution is more homogeneous. From such a comparison, the loading schedule design is effective in reducing the heterogeneity associated with die wall friction in die compaction.

Figure 13. Relative green density distribution after die compaction with new loading schedule.

SINTERING ANALYSIS

The sintering simulation relies on the input from the compaction simulation. Both the size and density distribution are key factors. To investigate how heterogeneity in green density effects distortion during sintering, the finite element simulation of the sintering process relied on input geometry and relative green density distribution from PMsolver/Compaction-3D. The material parameters associated with sintering the P25 cemented carbide powder were unknown. Accordingly, the material parameters for alumina as determined by Kwon et al. [8] were substituted for the P25 cemented tungsten carbide. Consequently, the quantitative distortion amount may not be the same as observed with the cemented carbide; however, the distortion behavior should be similar what is observed in practice. The sintering simulation was performed to attain full density.

Figure 14 compares distortion between the existing compaction loading schedule and our newly optimized compaction loading schedule. This figure color codes the displacement on the bottom surface in terms of vertical or z-directional motion after sintering. The distortion shown in Figure 14(a) reflects a significant industrial problem and even over 30% of the total production cost is used to grind out this distortion. The solution represented by Figure 14(b) reduces the peak bottom displacement and makes for a more homogeneous final size. The comparison of distortion amount shows that the pattern and amount of distortion depends on loading schedule used in die compaction and the distortion during sintering may be overcome through the proper selection of a loading schedule.
CONCLUSIONS

A new finite element solution is used to reduce sintered distortion of a die compacted and sintered cemented carbides cutting insert. An optimized tooling loading schedule in compaction was designed based on the goal to minimize green density gradients. Finite element simulation allowed for an efficient solution to determine the green density distribution in the powder compact. These finite element simulations were carried out using recently developed die compaction software, known as PMsolver. The reliability of the results was verified by comparing the green density solutions with results from ABAQUS. Superficial hardness tests allowed measurement of the actual green body density gradients for verification of the finite element predictions. With this success, the geometry and green body density gradients were used to predict sintering distortion. Distortion minimization was linked to the green density gradients. From the result of this study, we conclude that the tool loading schedule for the die compaction process can be adjusted to reduce the green body density gradients. In turn, the reduction in green density gradients helps lower distortion during sintering. Therefore, the proper selection of loading schedule can control the distortion.

However, the quantitative distortion amount predicted by the finite element simulation during sintering was not verified, since the material parameters for cemented tungsten carbide powders were not available. To precisely predict distortion amount, study is needed to extract the sintering parameters for the same material as used in the compaction simulation. In addition, to find the optimal compaction loading schedule requires optimization for the 3-D geometry instead of a simplified 2-D axisymmetric geometry. Finally, this study shows that final component distortion after sintering cannot be overcome through just a redesign of the compaction tool loading schedule. Rather, slight modification of die shapes is recommended, where the combined analysis of die compaction and sintering is essential. This approach involves the creation of new tooling and further optimization of tool motions. No attention has been
directed to changes in the sintering schedule that might minimize distortion, since green body density gradients are dominant factors in the current state of the press-sinter technology.

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