Numerical simulation and verification of hot isostatic pressing densification process of W-Cu powder

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Abstract
Based on finite element method (FEM) and the plasticity theory, a numerical model is built to simulate the hot isostatic pressing (HIP) process of W-Cu powders, and the densification law of the compact in the process is analysed. The cross-experiment method is used to formulate an orthogonal optimization plan for the insulation temperature, the holding pressure and the insulation holding time. The contour map diagram of the relative density in the temperature and pressure plane is established, and the optimal parameter scheme is proposed by simulation results. Experiments are carried out under the best HIP scheme. Comparison of experimental results with simulation results indicates that the numerical model is accurate. The results indicate that the densification process of the compact is from the edge to the centre. The optimal hot isostatic pressing parameter scheme obtained by simulation is 950 °C/110 MPa/2 h, and the overall relative density of the compact can reach more than 96% under this scheme. Under optimal scheme, the maximum error between the simulation results and the test results of the relative density is 1.28%, whereas the average error is about 0.3%.

1. Introduction
Due to the integrated properties of low coefficient of thermal expansion, electrical and thermal conductivities, wear and arc resistance, and high hardness, W-Cu alloy composed of high strength tungsten (W) and low melting point copper (Cu) phases are widely used in various fields [1–3]. The ideal microstructure of W-Cu alloy should consist of interpenetrating W and Cu networks with high densification and compactness [6, 7]. Although many new techniques have been employed in recent years to prepare denser alloy structures, there are still some challenges in improving the process.

Many novel techniques have been explored to improve the performance of W-Cu alloy [8–13]. These current technologies significantly enhance the performance and provide a good development for new materials, such as the study by Cai [14] shows that the tensile strength and plasticity of HIP (hot isostatic pressing) specimens are higher than those of SPS (spark plasma sintering) specimens. The HIP process can improve the mechanical properties of the product by reducing the porosity and recrystallizing microstructures [15]. Since HIP is carried out under the assistance of pressure, its sintering temperature can be reduced to close to the melting point of Cu, which significantly improves the sintering density. The advantages offered by HIP are well known. It can provide uniform density very close to theoretical density [16, 17]. However, HIP process of W-Cu alloy powder is a complex thermo-mechanical coupling process that combines material, geometric and contact nonlinearities. The powder in the HIP process is different from both fluid and dense body, and it changes in real time with the HIP process, so the forming process is difficult to solve by mathematical analysis. The exploration of a high efficiency and low cost manufacturing process is particularly important. In order to increase density of compact, it is a economic and scientific method to calculate and predict the behavior of powder before HIP experiments. The use of finite element analysis (FEA) to simulate the HIP process has been proved to be effective.
by researchers. These studies focused on the densification mechanism and the powder deformation. Numerical simulations about movement behavior of Ti6Al4V powder components have been reported by You [18] and Zhou [19], and the predicted configuration agrees well with the measured configuration. Hu [20] have also explored the densification behavior of tungsten alloy powder using numerical simulation during HIP process. However, there are few studies on the optimization of HIP process parameters using the numerical simulation.

The investigations based on the theoretical and simulation research of W-Cu alloy prepared by using HIP technology are quite still scanty. In the present study, the objective to obtain the optimal HIP experimental parameters by simulation before the HIP process experiment of WCu30 alloy compact. The finite element software DEFORM-2D is used to simulate the HIP densification process of W-Cu powders (WCu30). The aim of simulation is to study the effects of holding temperature, holding pressure and holding time on densification behavior of WCu30 powders and to optimize the HIP process parameters. Experiments are carried out under the optimal HIP scheme. The densification of the compact is tested and then compared with simulation results.

2. HIP experimental method

The experimental process of HIP of W-Cu powder in this paper is shown in figure 1. The purpose of optimizing the HIP process for W-Cu powder is to obtain the highest density using the optimal process parameters. The physical quantity to measure the test results is the relative density, and the density of W-Cu powders after the HIP process is used as the index of this test. The test factors include temperature, pressure and holding time, etc. According to the effect on the density of the W-Cu powder alloy, the primary factor can be determined to be the holding temperature, followed by the holding pressure and finally the holding time. According to the melting point of copper 1083 °C and the melting point of tungsten 3387 °C, the temperature starts 800 °C, and the level is set at 5 levels, with 50 °C interval for each level, for the pressure, according to the existing hot isostatic pressure equipment working range of 180 MPa, the minimum pressure is 70 MPa, and the level is set at 6 levels, with 10 MPa interval for each level. In addition, the minimum holding time is 1 h, 4 levels, each level interval of 0.5 h. The structural diagram of the can and powder is shown in figure 2, where the thickness of the side walls is 5 mm and the thickness of the base and lid is 10 mm.

HIP experiments were conducted on a SHIP 200-II hot isostatic press. The HIP experiments were conducted using the closed-mode compaction test setup in figure 3. The die is heated with a band heater and the temperature is measured with a thermocouple placed around the die. Both simulation and experiment adopt the same HIP process as shown in figure 4.

3. Numerical model

3.1. Mathematical model

3.1.1. Plasticity theory of alloy powder HIP

Based on continuum mechanics, the W-Cu alloy powder is regarded as a compressible continuum to describe the plastic deformation of the W-Cu alloy powder body. The plasticity theory of powder is mostly extended by the classical Von-Mises yield theory. Basic function of the powder yield criterion is defined as follows:
where $\alpha_1$ and $\alpha_2$ are functions of relative density, which can be determined by the boundary conditions shown in equation (2), $J_2'$ is the second invariant of stress bias; $J_1$ is the first invariant of stress, and $\sigma_s$ is the yield stress of the powder.
\[
\begin{align*}
\sigma_{\sigma_2,\sigma_3,\sigma_0} &= \sigma_1 \\
\frac{d\varepsilon_1}{d\sigma_1} &= \nu 
\end{align*}
\]  
(2)

where \(\nu\) is Poisson’s ratio; \(\varepsilon_1\) and \(\varepsilon_2\) are strains, and \(\sigma_1, \sigma_2\) and \(\sigma_3\) are space principal stresses.

From equations (1) and (2), relationship is obtained as follows:

\[
\begin{align*}
\alpha_1 &= \frac{2}{3}(1 - \nu) \\
\alpha_2 &= \frac{1}{3}(1 + 2\nu) 
\end{align*}
\]  
(3)

Substituting equation (3) into equation (1), the Kuhn yielding criterion can be obtained as follows:

\[
\sigma_0 = [3 f_2' - (1 + 2\nu) f_3']^{1/2}
\]  
(4)

where \(f_2\) is the second invariant of stress. Since the yield criterion of the powder can be represented by a rotating ellipsoidal surface on the principal stress space, the eccentricity \(e\) of this rotating ellipsoid can be obtained using equation (5). The centrifugal rate \(e\) determines the geometry of the yield criterion in the principal stress space and is therefore an important factor in the plastic deformation of the powder is one of the most important factors in the plastic deformation of the material [21].

\[
e = \sqrt{2\alpha_2/\alpha_1}
\]  
(5)

### 3.1.2. Contact and friction

It is significant to set contact conditions to determine the element motion, contact state and friction behaviour between the contacting bodies in the finite element analysis. Complex contact and friction problems caused by deformation of can and powder under high temperature and pressure during HIP process are important. In this work, the can and powder are set as deformable contacts, and the inner surface of the can contacts with the outer surface of the powder. The direct constraint method with high precision and good adaptability is selected as the contact algorithm. As there is both shear and slip friction in the HIP densification process of W-Cu powder, and along with the changes in temperature and pressure as well as density, the form of friction is also out of dynamic change, the more classical type of Coulomb friction is chosen as follows:

\[
\begin{align*}
\sigma_{fr} &\leq -\mu \sigma_n \\
\vec{t} &= \frac{\vec{v}}{||\vec{v}||}
\end{align*}
\]  
(6)

where \(\sigma_{fr}\) is the tangential friction stress, \(\sigma_n\) is the normal stress at the contact node, \(\mu\) is the friction factor, \(\vec{t}\) is the tangential unit vector in the direction of the relative sliding velocity, and \(\vec{v}\) is the relative sliding velocity vector. According to equation (6), the general Coulomb friction expression can be obtained as follows:

\[
\sigma_{fr} \leq -\mu \sigma_n \frac{\vec{v}}{||\vec{v}||}
\]  
(7)

However, in the process of powder particle forming, the contact state changes with the change of density at any time, resulting in the change of the size and direction of the friction velocity, which leads to the change of the size and direction of the friction force, and ultimately leads to the inaccuracy of the simulation results. Therefore, the modified Coulomb friction model based on the shortcomings of the classical Coulomb friction theory is utilized as follows:

\[
\sigma_{fr} \leq -\mu \sigma_n \frac{2\pi}{\tan^{-1}\left(\frac{||\vec{v}||}{v_c}\right)}
\]  
(8)

where \(v_c\) is the relative velocity between the critical contacts when relative sliding occurs.

### 3.2. Simulation model

According to the W-Cu alloy sample, the DEFORM-2D finite element software is used for the numerical simulations in the present work. The model is both symmetrical and a rotating body, which consists of a plastic can on the outside and a W-Cu alloy powder on the inside. To save simulation time, the finite element model is simplified to 1/4 of the model. As shown in figure 5, the mesh consists of the can and the powder, and the effects of porosity, assembly length and weld between the can cover and the sidewall are ignored.

Considering the complexity of the contact between the alloy powder and the plastic can, the local refinement method is used to refine the mesh of the powder boundary. The maximum mesh and minimum mesh size ratio
is adjusted to 2, and the relative refinement ratio is 0.1. The type II model consists of 1049 can elements and 1096 powder elements.

The initial relative density of the compact is 85%. The boundary conditions include the definition of symmetry plane and the history of temperature and pressure loading. According to figure 4, the temperature and pressure loads are applied directly on the external surface of the can, and the room temperature is set at 20 °C. Moreover, the can and the powder are defined as deformable contact bodies. The friction factor between powder and can is set to 0.36 and defined as sliding Coulomb friction [22]. In addition, the whole simulation process is divided into 1000 increment steps, each increment step is set to 1.4 s, which is solved by Newton-Raphson iterative algorithm.

3.3. Material parameters
The material parameters of the can are directly selected from the material library of DEFORM software as Q235 steel and set to fully dense deformable materials. The thermophysical parameters of W-Cu powder have been provided in table 1. According to the volume mixture model, under the premise of uniform particle distribution, the main parameters of W-Cu alloy powder can be calculated according to equation (9).

\[
\lambda = \lambda_0 \varphi_0 + \lambda_r \varphi_r
\]  

(9)

where \(\lambda\) is the parameter value of mixed phase, \(\lambda_0\) and \(\lambda_r\) are the parameter values of matrix and reinforced phase, and \(\varphi_0\) and \(\varphi_r\) are the volume fraction of matrix and reinforced phase respectively.

4. Results and discussions

To investigate the effects of different HIP parameters on the densification process, the densification behavior is discussed by analyzing the relative density distribution at typical moments and law curve of special nodes. Finally, the optimal HIP parameters are obtained, and the correctness of the simulation results is verified by experiments.

4.1. Densification analysis

Due to the uneven density distribution of compact during the densification process, the overall density of compact is difficult to characterize the densification law. Consequently, five key points are taken from the edge to the centre on the powder alloy compact shown in figure 7, and the densification pattern of these five nodes during the HIP process is studied separately. It comprehensively reflects the densification of different parts in the process of powder densification, which is convenient to investigate the densification law of compact under different HIP parameters.

4.1.1. Simulation results

After the HIP simulations for each scheme are completed, the M33 scheme (900 °C/90 MPa) is selected in table 2 to analyse the degree of densification of the compact at different moments. The relative density distributions of the compact at different moments under M33 scheme are analysed.

The relative density distributions of the compact at different moments during HIP process under the M33 scheme (900 °C/90 MPa) are shown in figure 6. Under the M33 scheme, when the HIP process is carried out at 1.0 h (2500 incremental steps), the temperature and pressure are increased to 600 °C and 60 MPa, respectively, and there is yet no significant densification behaviour in the compact. When the HIP process is carried out at 1.5 h (i.e., the temperature and pressure are increased to the holding temperature and pressure, respectively), a
Table 1. Main thermal and physical property parameters of tungsten, copper and WCu30 alloy.

| Element  | Thermal expansion coefficient \((10^{-6}/K)\) | Modulus of elasticity (GPa) | Poisson’s ratio | Electrical Conductivity (\(\Omega^{-1}\cdot\text{mm}^2\)) | Thermal conductivity (W/m\(\cdot\)K) | Heat capacity (J K\(^{-1}\)) |
|----------|-------------------------------------|-----------------------------|----------------|-------------------------------------------------|----------------------------------|---------------------|
| W        | 4.5                                 | 441                         | 0.28           | 18                                              | 174                              | 136                 |
| Cu       | 16.6                                | 145                         | 0.34           | 60                                              | 403                              | 385                 |
| WCu30    | 10.3                                | 352.2                       | 0.298          | 30.6                                            | 235.1                            | 210.7               |
significant densification behaviour occurs in the compact, and the relative density at the edge and the centre reached 97.24% and 86.96%, respectively. Hereafter, when the HIP process is carried out at 2.5 h, the heat preservation and pressure preservation have been completed, and the maximum relative density is 98.93%, which is distributed near the edge of compact, and the minimum relative density is 89.45%, which is distributed near the centre of compact. Finally, when the HIP process is carried out at 4 h, the whole HIP process has been completed, and the relative density of the minimum density area of the compact has reached 89.96%.

The results of relative density distribution in figure 6 show that different regions within the compact have different relative densities. Consequently, five key points has been taken to explore relative density distribution of compact from the edge to near the central axis. The five density measurement points selected from the compact are shown in figure 7. After 4 h of HIP, the relative density of the point 1 has reached more than 99%, while the point 5 has only reached 90%, and the relative density of the remaining points is distributed between 90% and 99%. In addition, the area near the edge of the compact first approaches complete densification, and the area near the axis of
the compact finally approaches complete densification. In other words, when point 5 is fully dense, the whole compact is fully dense. Therefore, only the relative density at point 5 needs to be measured and the relative density at that point 5 is employed as the reference point for optimization. It is worth noticing that the relative density of the whole compact is full dense when the relative density at point 5 achieves 96% or more.

Furthermore, the densification curve of the compact shows an ‘S’ shape as the HIP process proceeds shown in figure 7. At the initial stage of HIP, the relative density decreases slightly due to the increase in temperature, which causes the expansion of the plastic can and the compact. Hereafter, as the temperature and pressure increase, the compact reaches a rapid densification phase, which causes the movement and rearrangement of the larger particles and the filling of larger pores, with a rapid increase in relative density. During the pressure preservation stage, the compact undergoes viscoelastic deformation, the remaining small pores and defects in the compact are filled by extrusion, and the tendency of increasing relative density slows down. When the temperature and pressure are unloaded, the relative density of the compact increases by diffusion and creep.

4.1.2. Effects of HIP parameters on densification
To analyse the effects of HIP process parameters on the densification process of W-Cu powders, the process parameters (holding temperature, holding pressure, holding time) of HIP have been studied separately in this section to investigate the influence and law of each parameter on the densification process during the HIP process.

The variation of relative density for W-Cu compact with pressure at point 5 under different temperatures for holding time of 1 h is shown in figure 8(a), indicating that relative density at the edge of compact increases with pressure increasing. Obviously, there is a significant effect of temperature on the relative density of the compact after HIP. For example, the relative density at the edge of compact is 87% at 800 °C and 99.5% at 1000 °C under the pressure of 70 MPa and holding time of 1 h. It is worth noticing that the relative density at the edge of all compacts has achieved about 99%. Moreover, it can be seen from figure 8(a) that the higher the holding temperature, the higher the densification rate. This is because the higher the temperature of W-Cu powder during heat preservation, the lower the tensile strength of the particles is. Under the same pressure, the particles are more prone to plastic deformation and brittle fracture, forming smaller particles and filling more pores, which leads the compact denser. In addition, the viscosity between the powders decreases with the increase of temperature, so the smaller pressure can make the particles fracture into smaller particles, and the relative density reach the theoretical terminal density value in advance. The results are in accordance with Murray’s terminal density theory, where the effects of HIP temperature on relative density increase exponentially and are more significant than the effects of pressure on relative density.

Table 2. Optimizing programs of HIP process parameters for W-Cu alloy powder.

| Temperature/°C | Pressure/MPa | 70  | 80  | 90  | 100 | 110 | 120 |
|---------------|--------------|-----|-----|-----|-----|-----|-----|
| 800           | M11          | M12 | M13 | M14 | M15 | M16 |
| 850           | M21          | M22 | M23 | M24 | M25 | M26 |
| 900           | M31          | M32 | M33 | M34 | M35 | M36 |
| 950           | M41          | M42 | M43 | M44 | M45 | M46 |
| 100           | M51          | M52 | M53 | M54 | M55 | M56 |

Figure 8. Relative density of point 5 after keeping at different HIP parameters: (a) relative density of point 5 after keeping at different temperatures for holding time of 1 h, (b) relative density of point 1 after keeping at different pressures holding time of 1 h and (c) relative density of point 5 after keeping under holding times of 1-2.5 h.
The variation of relative density for compact with temperature under different pressures for holding time of 1 h is shown in figure 8(b). During the HIP densification process of W-Cu powders, the effects of pressure on density are smaller compared to the effects of temperature on density. The relative density of compact is 87.1% under low pressure of 70 MPa and 99% under pressure of 120 MPa at 800 °C, which increases by 8.7%. In addition, at lower temperatures, the densification rate varies almost linearly with temperature before the plastic deformation of the powder particles occurs, which increases rapidly due to the rearrangement, the translation and rotation of the powder particles under pressure. When the temperature reaches above 900 °C, the densification rate decreases, and the densification rate varies nonlinearly with temperature. However, the higher the pressure after 900 °C, the lower the densification rate, which means that a right pressure must be chosen within a certain temperature range. If a higher pressure is chosen, the densification rate decreases during the plastic deformation phase and the overall densification time increases. If a smaller pressure is chosen, the time of the particle rearrangement phase is increased. Therefore, it is important to select the appropriate HIP pressure for the densification rate of W-Cu powder without considering the holding time.

Figure 8(c) shows the variation of relative density for compact at point 5 with pressure under different holding time, indicating that the relative density of W-Cu powder increases with increasing holding time and that a longer holding time results in less pressure being required to achieve the same relative density, and the results show that there is likeness compared with the law that the higher the temperature, the smaller the holding pressure required to reach the same relative density. Consequently, the heat preservation and pressure preservation stage are the most important process in the densification process of powders, which can prevent the arc ablation of high voltage electrical contacts due to those tiny pores and defects, and is also the core technology to improve the service life of powder alloy. To prepare dense W-Cu alloy products, the holding stage is crucial, where the densification rate is slow, but the densification density is close to complete densification. In other words, extending the holding time during the HIP densification process can further improve the densities of the compact and the properties of the W-Cu alloy products. Therefore, based on the analysis of the numerical simulation results, the holding time of WCu30 can be 1.5 h to 2.5 h under the premise of ensuring the qualified performance of the products, without considering the influences of temperature and pressure.

4.1.3. Optimization of HIP parameters

According to the results from section 4.1.2, when a lower holding temperature (800 °C) is chosen, a higher holding pressure (120 MPa) is required to bring the compact close to full density, while when a lower holding pressure (70 MPa) is chosen, a higher holding temperature (1000 °C) is required to bring the compact close to full compaction. Consequently, the three parameters (holding pressure, holding temperature and holding time) of the HIP process are optimized simultaneously in this section. The crossover schemes are shown in table 2, where are 120 schemes for the HIP process according to the permutations of five temperature values and six pressure values set by the initial and boundary conditions, plus four holding times. In these schemes, the minimum holding temperature, minimum holding pressure and minimum holding time are optimized according to the densification law of section 4.1.2, using the relative density of compact at the point 5 as the target value for optimization.

As shown in figure 9, the surfaces of relative density versus holding temperature and holding pressure are plotted using the response surface methodology (RSM), based on the data from the simulation results of the
schemes in Table 2, with surfaces stacked under holding time of 1–2.5 h. The relative density of the point 5 changes less with the holding temperature when the holding time is 1 h, which is because the holding time is too short, the temperature and pressure act almost exclusively on the edge of compact. When the temperature and pressure act on the point 5, the effect has been significantly reduced, resulting in smaller effects of holding temperature on the relative density in the central region of compact. It can be seen from Figure 9 that when the holding temperature exceeds 900 °C, the higher the holding temperature, the smaller the holding pressure required if the compact achieves the same relative density. Moreover, the relative density of compact above 96% in the figure 9 corresponds to a wide range of holding temperatures and pressures. When the holding temperature is higher than 900 °C and the holding pressure reaches 100 MPa, the relative density of compact is 95% to 97%, but not all of them reach above 96% when the holding time is 1.5 h. However, when the holding time is 2 h under holding temperatures of 900 °C and holding pressures of 100 MPa to 120 MPa, the relative density of compact can reach 96% to 98%. In addition, when the holding time is 2.5 h, the relative density of compact can reach 96% of the holding temperature and holding pressure ranges are the widest, but the holding time is the longest.

In summary, in the HIP scheme of W-Cu alloy powder, the relative density can reach more than 96% in the following parameters: holding temperatures of 900 ~ 1000 °C, holding pressures of 100 ~ 120 MPa, holding times of 1.5 ~ 2.5 h. Table 3 shows the relative density of point 1, 2, 3, 4 and 5 under the three optimized parameters schemes. According to the principle of energy saving and high efficiency, the optimized solutions is holding temperature of 950 °C, holding pressure of 110 MPa and holding time of 2 h. Figures 10(a)–(d) shows the relative density of the compact after HIP for holding times of 0.5, 1, 2 and 3 h under the optimized scheme of (950 °C, 110 MPa). From figure 10(e), the overall relative density of the compact can reach more than 96% at 4 h of HIP. From figure 10(f), the

![Figure 10](image)

**Figure 10.** Relative density distributions (a–e) of compact for different times of HIP process and the variation (f) of relative density of different points with time under program M45 scheme (950 °C/110 MPa).

**Table 3.** Relative density of five points under three kinds of optimized parameter programs (%).

| Scheme               | P1   | P2   | P3   | P4   | P5   |
|----------------------|------|------|------|------|------|
| 900 °C/100MPa/1.5h   | 99.49| 97.42| 93.87| 93.16| 92.94|
| 950 °C/100MPa/2h     | 99.99| 99.91| 98.36| 97.38| 97.03|
| 1000 °C/100MPa/2.5h  | 100  | 100  | 100  | 99.99| 99.89|

schemes in Table 2, with surfaces stacked under holding time of 1–2.5 h. The relative density of the point 5 changes less with the holding temperature when the holding time is 1 h, which is because the holding time is too short, the temperature and pressure act almost exclusively on the edge of compact. When the temperature and pressure act on the point 5, the effect has been significantly reduced, resulting in smaller effects of holding temperature on the relative density in the central region of compact. It can be seen from figure 9 that when the holding temperature exceeds 900 °C, the higher the holding temperature, the smaller the holding pressure required if the compact achieves the same relative density. Moreover, the relative density of compact above 96% in the figure 9 corresponds to a wide range of holding temperatures and pressures. When the holding temperature is higher than 900 °C and the holding pressure reaches 100 MPa, the relative density of compact is 95% to 97%, but not all of them reach above 96% when the holding time is 1.5 h. However, when the holding time is 2 h under holding temperatures of 900 ~ 1000 °C and holding pressures of 100 ~ 120 MPa, the relative density of compact can reach 96% to 98%. In addition, when the holding time is 2.5 h, the relative density of compact can reach 96% of the holding temperature and holding pressure ranges are the widest, but the holding time is the longest.

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relative density of point 5 can reach more than 96% when HIP process is carried out for 4 h. According to the law described in section 4.1.1, the relative density of the whole compact has reached more than 96%.

4.1.4. Experimental verification of simulation results

The compact after HIP is shown in figure 11. The compact is cut into 2 mm thick slices along the axial direction, and five sampling points are marked in the simulation. Five specimens are taken out from these five points, and the relative density is measured by Archimedes drainage method. Hereafter, the average relative density is calculated as follows:

$$\rho = \frac{m_1 \rho_d}{m_1 - m_2}$$

where $\rho_d$ is the density of distilled water. The relative density results of the experiment and simulation are comparatively analysed, as shown in table 4.

As shown in table 4, the average relative error in relative density between the simulation and experiment is 0.30%. There is no significant difference between the experimental results and the simulation results of the compact in terms of the relative density, which indicate that the numerical model is reasonable.

4.2. Microstructural analysis

The microstructure of WCu30 alloy before and after the HIP experiment as determined by scanning electron microscopy (SEM) are shown in figures 12(a) and (b), where the HIP experimental parameters are those optimized according to the simulation, which illustrate that the optimized HIP scheme greatly impact the compact microstructure. To confirm the phase constitution further, the WCu30 specimen after HIP was characterized by TEM shown in figure 12(c). There are two distinct regions, greyish-white area (area A) and greyish-black area (area B). The electron diffraction patterns and calibrations of the area A and area B in figures 12(d) and (e) indicate that the grey-white ellipsoidal shape is the tungsten phase and the grey-black shape is the copper phase, and the remaining dark black is the pore space.

Comparing figures 12(a) and (b), it can be found that the distribution of tungsten and copper phases in the W-Cu alloy compact before HIP is not uniform, there are copper phases enriched areas, and many pores in the alloy. However, the distribution of tungsten and copper phases in the W-Cu alloy compact after HIP is significantly better than the distribution of tungsten and copper phases before HIP. There is no copper phase enrichment in the alloy, and the tungsten particles do not grow significantly. Moreover, the number of pores is greatly reduced and the density increases significantly, indicating that the optimization of the HIP process by means of finite element numerical simulations results in a homogeneous and dense tungsten-copper alloy.

### Table 4. Experimental and simulated relative density of compact at different point (%).

| Scheme | P1   | P2   | P3   | P4   | P5   | Average |
|--------|------|------|------|------|------|---------|
| Simulation | 99.99 | 99.83 | 98.08 | 97.30 | 97.03 | 98.45   |
| Experiment | 100  | 100  | 98.6  | 96.4  | 95.8  | 98.16   |
| Error/% | 0.01 | 0.17 | 0.53  | 0.93  | 1.28  | 0.30    |

Figure 11. Compact after HIP: (a) with can and (b) without can.
5. Conclusions

The influences of holding temperature, holding pressure and holding time on the densification process during HIP are investigated by finite element simulations. The HIP process parameters are optimized by the FEM simulation results and both simulation and experiment have been carried out under the optimal scheme. The conclusions could be drawn as follows:

1. During the HIP process, the relative density of WCu30 alloy compact decreases from edge to the center in decreasing order.

2. The effect of temperature on the relative density of the compact is more pronounced in the heat preservation stage, where the temperature increasing results in a lower rheological stress in the alloy and a higher temperature makes it easier to dense the billet at the same pressure.

3. The heat preservation and pressure preservation stage are the most important step in the densification process, and extending the holding time during the HIP process can further improve the relative density of WCu30 alloy compact.

4. The best HIP process parameters scheme for WCu30 alloy is 950 °C/110 MPa/2 h, and the overall relative density of the compact can reach more than 96% under this scheme. The maximum error between the simulated results and experimental results of the relative density for the compact is 1.28% when the HIP test is conducted under the best scheme.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Credit authorship contribution statement

Yuanjun Wang: Conceptualization, Methodology, Software, Data curation, Visualization, Writing - review & editing, Investigation, Validation. Fazhan Wang: Writing—original draft, Project administration, Funding acquisition, Supervision. Yixuan Wang: Translation, Grammar check.

Declaration of interest statement

The authors report there are no competing interests to declare.

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