

Numerical simulation of canned extrusion process of the W-25wt. %Cu composites under low temperature and liquid sintering

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Abstract. The W-25wt. % Cu compacts prepared by low temperature vacuum sintering (sintering at 1090°C), and then hot extrusion under low temperature and canning backward extrusion (extrusion temperature is 1090°C, extrusion ratio is 7.7), finally annealing at 900°C have better properties. The defects such as fracture and canning cracking and the low utilization rate of materials due to the uneven distribution of the W-Cu materials along the longitude were solved by the numerical simulation of the hot extrusion process of the billet and defect analysis in the canning backward extrusion process. The good coincidence of the distribution of the W-Cu materials and the loading force in the hot extrusion experiment with the numerical simulation results proved the accuracy of the model and parameter selection in numerical simulation. So the simulation results have practical significance. The results show that canning cracking was mainly due to the difference strain and flow speed between the canning and the W-Cu billet, while the flow of the W-Cu billet was affected by the structure and material of the canning. It is concluded that when the extrusion temperature was near the melting point of copper phase, the extrusion speed was in the range of 5 to 10 mm/s, extrusion ratio was in the range of 7.7 to 11, the canning thickness was 5 mm and material was AISI-1016 can not only improve the temperature and stress and strain distribution of billet and canning but also enhanced the flow uniformity of billet.

1. Introduction

The rapid development of high-end area of electronic communication, aerospace and national defense industry has made the tungsten-copper composites with more excellent properties, such as higher intensity and better air tightness (which ask for the relative density is not less than 98%), more uniform composition and microstructure, more excellent thermoelectric properties and lower thermal expansion coefficient. It is necessary to promote the development of new preparation and synthetic process technology of the tungsten-copper composites [1-5].

The most common method of producing tungsten-copper composites is the pressureless infiltration technique and liquid-phase sintering method [6]. The pressureless infiltration technique is always used to prepared the tungsten-10~40 wt.% copper composites with macrograin [7, 8]. As to the liquid-phase sintering method, the densification process is mainly through the rearrangement of tungsten particles and solid phase sintering of tungsten skeleton owing to the poor intersolubility of tungsten and copper



element [9]. When the content of liquid copper up to 40 wt.% [10], the W skeleton is still difficult to deform [11, 12]. It is not easy to obtain compact tungsten and copper composites. Moreover the huge difference of melting point between tungsten and copper element caused to the composition uncontrollability of the tungsten copper sintered compacts. According to the research of Guo Shu, the content of liquid copper is 30wt.% the copper begin to loss. When the content of liquid copper is up to 50wt.% , the loss of the copper up to 10wt.% [13]. Therefore, it is of little significance to improve the densification degree of tungsten-copper composites by simply using higher sintering temperature.

In recent years, to solve the densification of tungsten-copper composites, scholars around the world have taken a large number of basic and theoretical studies on the structure, synthesis/preparation and processing of tungsten-copper composites and their relationship with their performance. The results indicated that sub-micron tungsten copper powders with great activity and advantage, can improve the densification process of tungsten-copper composite material [14-18]. And the higher content of tungsten materials, the more dependent on the particle size [9].

To obtain the high quality of tungsten-copper sintered compacts, in this paper the ultra-fine tungsten copper powder is sintered by low temperature liquid phase sintering, and then canned hot extrusion [19]. While in the process of the experiment, there are many problems such as cracking, fracture of the steel jacket (as shown in figure 1) and low material utilization owing to the uneven distribution of copper along the axis. Therefore, the canned extrusion process of the W-25wt. %Cu composites under low temperature and liquid sintering is numerical simulated using the DEFORM software simulation to shorten the experimental process [20].

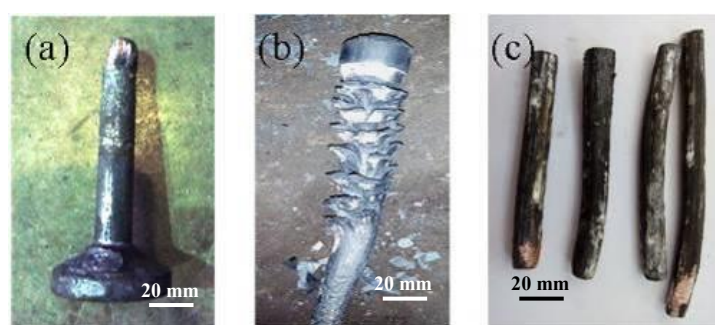


Figure 1. The defects in the process of extrusion: (a) fracture of the extrusion billet; (b) crack of the 45 steel jacket and (c) tungsten copper material extrusion out first and then fracture.

2. Experimental procedures

2.1. The raw materials

First, nano-sized tungsten copper composite powder contains 25 wt. % copper was synthesized by hydrothermal method; and then was processed by low temperature liquid phase sintering and canning backward extrusion; finally, the high density ultrafine W-Cu composites were obtained. It is concluded that when the extrusion temperature and the preheat temperature was near the melting point of copper phase (1030, 1050, 1070, 1090 or 1120°C), the extrusion speed was in the range of 2 to 10 mm/s (2, 5, 10 or 15 mm/s), extrusion ratio was in the range of 5.2 to 17.4 (5.2, 7.7, 11 or 17.4) [21].

2.2. The parameters of the numerical simulation process

In order to ensure the accuracy of the simulation results and the consistency with the experimental results, the appropriate flow stress, thermal physical property parameters, interface heat transfer coefficient and friction factor of tungsten copper material should be used.

The real stress-strain curves of W-25wt. %Cu sintering billet were measured by Gleeble-1500 thermal simulator. The constitutive equation of W-25wt. %Cu composite material was calculated as the Equation 1 [21].

$$\dot{\varepsilon} = 1.29 \times 10^{15} [\sinh(0.00488\sigma)] \exp[-317.15 \times 10^3 / (RT)] \quad (1)$$

Because the heat capacity is not affected by the microstructure of the material, the heat capacity C_{comp} of the tungsten copper material can be calculated according to the law of the mixture as the Equation 2 [22, 23]:

$$C_{\text{comp}} = W_{\text{Cu}} C_{\text{Cu}} + W_{\text{W}} C_{\text{W}} \quad (2)$$

Where the W_{Cu} , W_{W} is the weight percent of copper and tungsten respectively; C_{Cu} , C_{W} is the specific thermal capacity of copper and tungsten respectively, and the C_{Cu} , C_{W} is 385, 136 J/(kg·K) respectively [21]. So the specific thermal capacity of W-25wt.%Cu is 198.25 J/(kg·K).

According to the theoretical calculation formula of thermal expansion coefficient (α_T) proposed by German [22, 23].

$$\alpha_T = \alpha_{\text{Cu}} + \frac{\alpha_{\text{W}} - \alpha_{\text{Cu}}}{1 + \frac{B_{\text{Cu}}}{B_{\text{W}}} \left[\frac{8R - 8R^2}{1 - 2R^2} - \frac{(1 - 2R)\pi R^2}{1 - \pi R^2} \right]} \quad (3)$$

$$R = 0.0113 + 1.58V_{\text{Cu}} - 1.83V_{\text{Cu}}^{3/2} + 1.06V_{\text{Cu}}^3 \quad (4)$$

$$B_i = \frac{E_i}{3 \times (1 - 2\gamma_i)} \quad (i = \text{Cu, W}) \quad (5)$$

Where the α_{Cu} , α_{W} is the coefficient of thermal expansion of copper and tungsten respectively; B_i is the volume modulus of each component; γ_i is the Poisson's ratio of each component; E_i is the elasticity modulus of each component; V_{Cu} is the volume fraction of copper. So the coefficient of thermal expansion of W-25wt.%Cu is 9.7 ppm/K.

According to the theoretical calculation formula of thermal conductivity (Q_T) proposed by German [22, 23].

$$Q_T = \pi R^2 Q_{\text{Cu}} + (1 - 2R)^2 Q_{\text{W}} + \frac{Q_{\text{W}} Q_{\text{Cu}} A_L}{3/2 R Q_{\text{W}} + (1 - 3/2 R) Q_{\text{Cu}}} \quad (6)$$

$$A_L = 4R(1 - R) - \pi R^2 \quad (7)$$

Where Q_{W} , Q_{Cu} is the thermal conductivity of copper and tungsten respectively; R is calculated by Equation 7. So the thermal conductivity of W-25wt.%Cu is 284 W/(m·K).

German assumes the material without strain, porosity, and with the ideal interface combining. And in fact, the residual stress and porosity in the material could affect the thermal conductivity. Kohn and Fortini estimate the influence of porosity on the thermal conductivity as the Equation 8 [24].

$$Q_r = \frac{1 - \varepsilon}{1 + 11\varepsilon^2} Q_c \quad (8)$$

Where Q_r , Q_c is the actual and theoretical thermal conductivity of the material respectively, ε is the porosity of the material. ε is calculated by Equation 9.

$$\varepsilon = (1 - \frac{\rho_0}{\rho}) \times 100\% \quad (9)$$

Where ρ_0 , ρ is the actual and theoretical density of the material respectively.

The density of W-25wt.% Cu sintered compacts is 92%, so ε is 8%. After correction, the thermal conductivity of W-25wt.% Cu is 244 W/(m·K).

The heat transfer coefficient between the W-25 wt. % Cu and air is 0.021 N/(s·mm·°C), and the heat transfer coefficient of the mould is 11 N/(s·mm·°C) [22]. The temperature at the time of extrusion is measured with an infrared thermometer. When the melt temperature is 1030°C, 1050°C, 1070°C, 1090°C and 1120°C; the coating temperature is 790°C, 804°C, 818°C, 830°C and 845°C respectively.

2.3. Numerical simulation model of canned extrusion process

In the process of simulation, the geometrical shape of the upper die (extrusion die); the lower die (container) and the billets are determined; especially for extrusion die Angle (which is set as 60°). The model is simplified to 2D and the one-half structure owing to the extruded blank is symmetric about

the z axis. The process of the extrusion and the sketches of the billet were shown in figure 2. The bottom and wall thickness of the steel sleeve is fixed to 10mm and 5 mm. Tungsten-copper materials are defined as porous material. The package is defined as a plastic body, and the upper and lower die are defined as rigid bodies. The top of the package is set to 2, 5 or 10 mm. The package material is an important factor in the extrusion process considering the cost of the experiment; the steel sleeve is made of the common carbon structural steel (AISI-1016, AISI-1045 or AISI-1060).

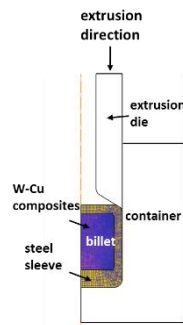


Figure 2. The process of the extrusion and the sketch of the billet.

3. Numerical simulation of canned extrusion process

The phenomenon crack of the steel sleeve occurred in the process of heat extrusion. When change the thickness of the steel sleeve, the "big head" and "small head" phenomenon occurred due to the uneven distribution of copper along the axis. So the material utilization is low. Figure 3 indicated the effects of top thickness and materials of steel jackets on the hot extrusion simulation results and the billet shape. When the top thickness of the steel sleeve is 2mm, the steel sleeve cracked and the "big head" occurred (figure 3 a~c). When the top thickness of the steel sleeve is 5mm, the steel sleeve cracked is slightly in AISI-1045 steel jackets, but the distribution of copper along the axis is even (figure 3 d~f). When the top thickness of the steel sleeve is 10mm, the steel sleeve is not cracked and the "small head" occurred (figure 3 g~i). In order to describe the crack of the steel sleeve more accurately, such as the fracture position and after fracture the continuous of the deformation. The formation processes of the steel jackets (2 mm, AISI-1016) was analysed (figure 4). The steel sleeve first breaks at the die gate (figure 4 c). And then the material below the die gate will continue to deform until the simulation is over. Figure 5 shows the changes of damage coefficient, temperature, stress-strain and velocity field with the extrusion time of the inside and outside of the billet and steel jacket. According to the strain and velocity curve and the damage coefficient, it can be seen that the crack of the steel sleeve is mainly related to the strain and velocity difference of billet and steel jacket (figure 5 e, f). Therefore, in order to ensure the good surface quality of the compacts, the uniform strain and velocity field is important.

The effects of the jacket thickness and materials on the temperature, stress, strain and velocity field were shown in figure 6 and figure 7. The results show that the canning thickness was 5 mm and material was AISI-1016 can not only improve the temperature and stress and strain distribution of billet and

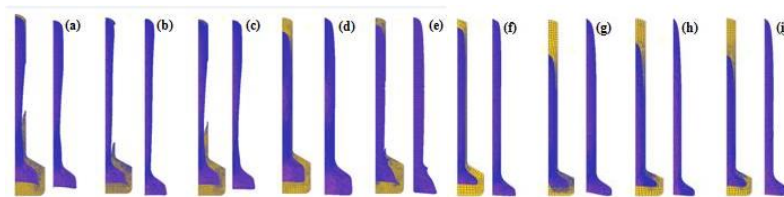


Figure 3. Effects of top thickness and materials of steel jackets on the simulation results: (a) 2 mm, 1016; (b) 2 mm, 1045; (c) 2 mm, 1060; (d) 5 mm, 1016; (e) 5 mm, 1045; (f) 5 mm, 1060; (g) 10mm, 1016; (h) 10 mm, 1045; (i) 10 mm, 1060.

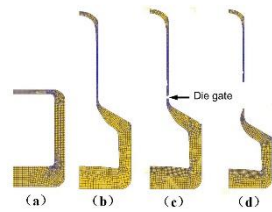


Figure 4. The formation processes of the steel jackets in the extrusion process.

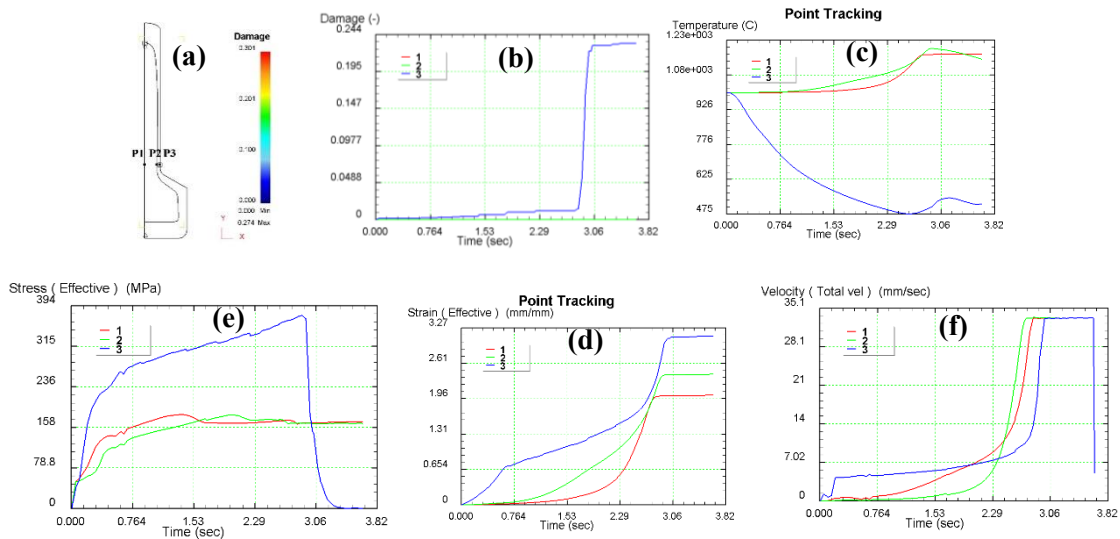


Figure 5. The changes of damage coefficient, temperature, stress-strain and velocity field with the extrusion time of the inside and outside of the billet and steel jacket: (a) the locations of point tracking point; the curves of (b) damage coefficient; (c) temperature; (d) stress; (e) strain and (f) velocity field.

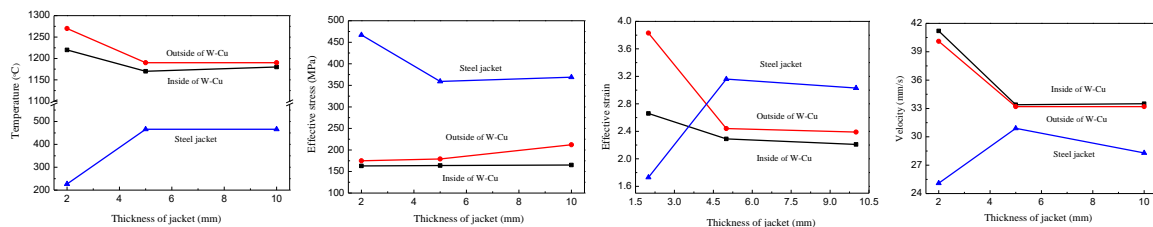


Figure 6. The effects of the jacket thickness on the temperature, stress, strain and velocity field.

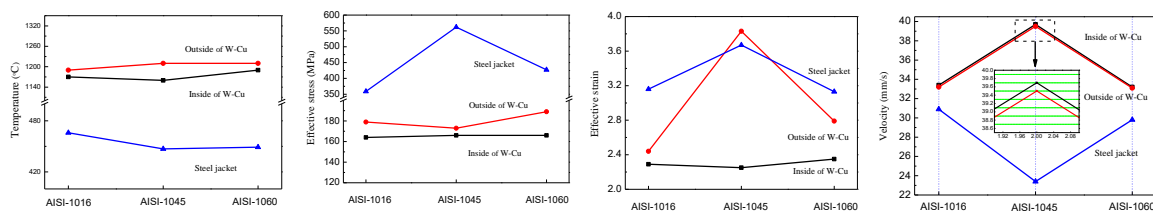


Figure 7. The effects of the jacket materials on the temperature, stress, strain and velocity field canning but also enhanced the flow uniformity of billet. Which is consistent with results hot extrusion simulation results and the billet shape (figure 3).

4. Result validations

Figure 8 shows the products and the shape of the numerical simulation of the extrusion billet, when the coating thickness is 5 mm, material was AISI-1016, extrusion temperature is 1090°C, extrusion ratio

7.7, the extrusion speed of 5 mm/s. It can be seen that the copper distributed uniformly along the axis and are consistent with the numerical simulation.

Figure 9 shows the comparison of the load between the simulation and experimental value at different extrusion temperatures and extrusion ratios. The difference of the load between the simulation and experimental value are not more than 5%. So the results can be determined the the accuracy of numerical simulation. While the trend of load value between the simulation and experimental value is different, and the inflection point is when the extrusion temperature is 1080°C. When the extrusion temperature higher than the melting point of copper, the actual load force less than that of numerical simulation, this is mainly because the copper melting promoted the rearrangement of tungsten particle. The actual load force is higher than that of numerical simulation, this is mainly due to the time remove from heat treatment furnace billet to begin to extrusion in the actual process of hot extrusion needed slightly longer than the set value. So the practical extrusion temperature is lower than the temperature of the parameters set by the numerical simulation.

The good coincidence of the distribution of the W-Cu materials and the loading force in the hot extrusion experiment with the numerical simulation results proved the accuracy of the model and parameter selection in numerical simulation. So the simulation results have practical significance.

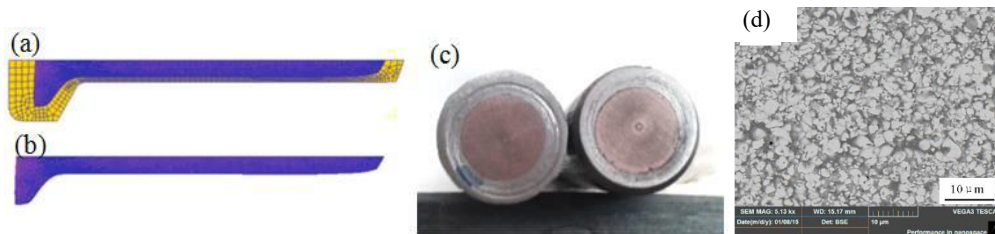


Figure 8. W-Cu extrusion billet: (a and b) simulation; (c) experimental products (d) microstructure of the W-Cu composite.

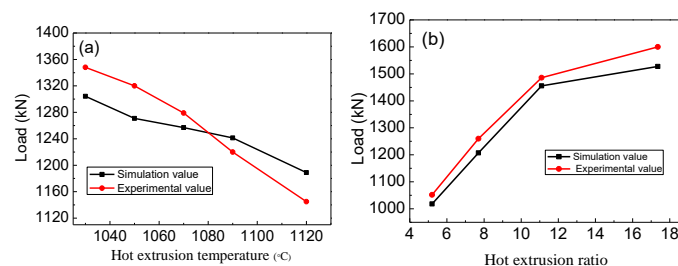


Figure 9. Comparison of the load between the simulation and experimental value: (a) at different extrusion temperatures and (b) at different extrusion ratio.

5. Conclusions

(1) The crack of the steel sleeve is mainly related to the strain and velocity difference of billet and steel jacket. The uniformity of velocity was mainly affected by the structure and material of the steel jacket.

(2) It is concluded that when the extrusion temperature was near the melting point of copper phase, the extrusion speed was in the range of 5 to 10 mm/s, extrusion ratio was in the range of 7.7 to 11, the canning thickness was 5 mm and material was AISI-1016 can not only improve the temperature and stress and strain distribution of billet and canning but also enhanced the flow uniformity of billet.

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