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ARTICLE

Plastic Deformation and Densification Behavior By Different Sheath Materials in Molybdenum Powder Forging

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Abstract: Finite element method (FEM) was used to investigate the plastic deformation and densification for porous molybdenum in isothermal canned forging. Separate simulations were performed using different sheath materials: 45 steel, 304 stainless steel and GH4169. The simulations demonstrate that the distributions of strain, density and average stress strongly depend on the sheath materials. The distributions of density and strain present the shape of "U". The density and strain, increase with increasing strength for sheath materials at the same levels of deformation. The homogeneity of strain and density are best in billet encapsulated with the 304 stainless steel when the deformation extent exceeds 40%. The average stress decreases linearly with the increasing distance from center except for small area near the edges. Among the three materials, the 304 stainless steel is the most suitable materials as sheath during isothermal canned forging of porous molybdenum.

Key words: porous molybdenum; canned forging; sheath material; FEM

Molybdenum has been taken seriously as a rare metal of strategic significance, for its high strength, high Young's modulus, excellent conductivity, high melting temperature and low linear coefficient of thermal expansion[1,2]. It is widely used in industrial applications, such as vacuum furnaces, electrode plates, defense missiles and jet engines[3]. However the major obstacles for engineering applications are its high deformation resistance, low toughness, high brittleness and poor temperature oxidation resistance. From the consideration on the economy, powder metallurgy has been used for 90% of Molybdenum and its alloys. But because the process is difficult to control in the high temperature heating, there are many quality problems in the traditional process, such as splitting, stratification, and the decrease of intensity. And the microstructure and performance are easy to produce clear anisotropic. Thus, traditional method can't satisfy the demand of production use. In recent years, the warm compaction[4], equal-channel angular pressing (ECAP)[5], hot isostatic process (HIP)[6] have been used to promote powder metallurgy densification and deformation. They solve many problems, but also have their limits[7].

A novel technology is investigated for manufacturing molybdenum products in this study. It combines the isothermal forging [7] and canned powder forging[8]. The billet is encapsulated in metallic sheath, and then deformation takes place simultaneously during isothermal forging. So the billet is subjected to severe compressive stresses and the deformation capacity is improved greatly. At the same time, the oxidation phenomenon can be avoided. Thus the formation of crack can be prevented. And because it is one-step molding, the utilization and the efficiency are improved. It should be noted that there is coordinating deformation between the billet and sheath. Thus the systematic investigation indicated that homogeneous deformation is strongly related to the sheath materials.

On the basis of above research, the objective of this study is to investigate the influence of densification and plastic flow on the sheath materials based on the FEM.

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1 Experiment

Isothermal FEM simulations of the canned forging were performed using the rigid-plastic FEM DEFORM-2D software, version 6.1 [Scientific Forming Technologies Corporation, Columbus, OH]. The finite element model is shown in Fig.1.

Due to axial symmetry around the central axis, the calculation was simplified by a two dimensional model. The dies are considered as rigid body and no deformation is permitted. However, the sheath and billet are considered as rigid-plastic and porous bodies, respectively.

There were two stages during the canned forging process. Firstly the billet was taken out of the heating furnace and transferred to the dies rapidly. The heat transfer time between the billets and environment was 10 s. Consequently, the billet was being upset. The initial simulation parameters are shown in Table 1. Three different sheath materials were used (45 steel, 304 stainless steel, and GH4169). The sheath materials properties (stress-strain curve) used in present simulations are taken from previous studies[9-11]. The shear contact friction was used in this model.

2 Results and Discussion

2.1 Effect of sheath materials on densification

The density being attained of as-forged billet plays an effective role in determining the product properties. Due to the substantial amount of porosity content in P/M parts, the mechanical properties are easily to deteriorate. It is reasonable to anticipate that higher values of relative density in any particular area of the billet show better mechanical properties in this area. Fig.2 shows the distribution of relative density on the cross-section of billet after processing by the canned forging. It is observed that the distribution of the highest densities is located in the centers of the billet and the densities decrease with the increasing distance from the center along the radius for all simulations, especially the billets covered with 45 steel and 304 stainless steel. The higher densities attribute to the higher average stress generated by the sheaths. By contrast, the distinction in density among billets with different sheath materials is the percentage of high density. It is clearly released that the billet encapsulated with GH4169 in Fig.2c achieves near full density. However, the percentage of high densities (⩾0.995) in billets encapsulated with 45 steel and 304 stainless steel are nearly 30% and 70%, respectively. This result is reasonable because the GH4169 is harder to deform compared to other materials. Thus this leads to a huge compressive stress state inside the billet, which is benefit to densification. The present simulations suggest the higher strength which the sheath materials obtain, and the higher densification the billets achieve.

In order to analyze the effect of sheath materials on the density homogeneity of billets qualitatively during processing, the density inhomogeneity index, D_{in}, is introduced. It is simply defined by the following formula.

$$D_{\mathrm{in}} = \frac{D_{\max} - D_{\min}}{D_{\mathrm{avg}}} \tag{1}$$

Where $D_{\max}$, $D_{\min}$ and D_{avg} are the maximum, minimum and average relative density of the billet, respectively. Fig.3

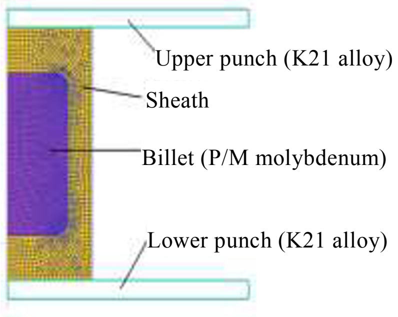

Fig.1 Finite element model

Table 1 Simulation parameters

Simulation parameter	Value	Simulation parameter	Value
Billets size	Φ30 mm×36 mm	Environment temperature at the second stage/℃	1000
Cumulative reduction/%	80	Heat transfer coefficient with the environment/W·(m^2·K)$^{-1}$	21
Sheath wall thickness/mm	6	Heat transfer coefficient between sheath and die/ W·(m^2·K)$^{-1}$	2000
Sheath bottom thickness/mm	10	Heat transfer coefficient between sheath and billet/ W·(m^2·K)$^{-1}$	2000
Forging rate/mm·s^{-1}	3	Friction coefficient between sheath and die	0.3
Initial temperature of the billets/℃	1050	Friction coefficient between sheath and billet	0.7
Initial temperature of the die/℃	1000	Step length at the first stage/s	0.1
Environment temperature at the first stage/℃	20	Step length at the second stage/mm	0.1