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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.

$$D_{in} = \frac{D_{max} - D_{min}}{D_{avg}} \quad (1)$$

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

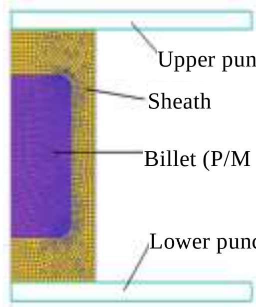

Fig.1 Finite element model

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

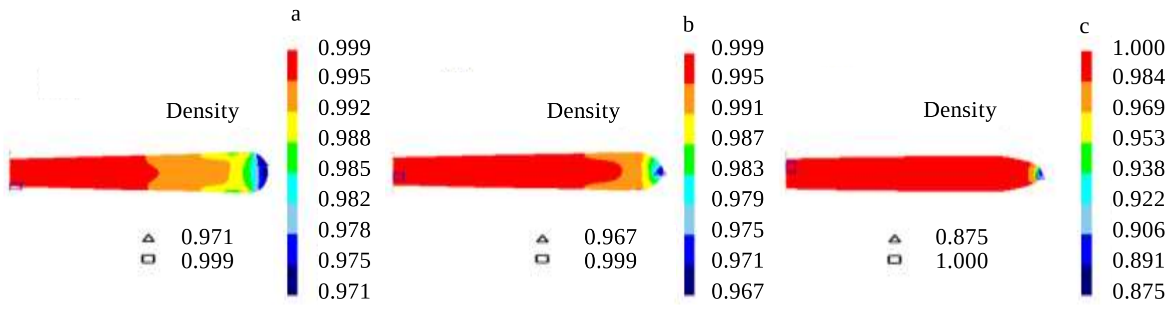

Fig.2 Distribution of relative density with different sheath materials: (a) 45 steel, (b) 304 stainless steel, and (c) GH4169

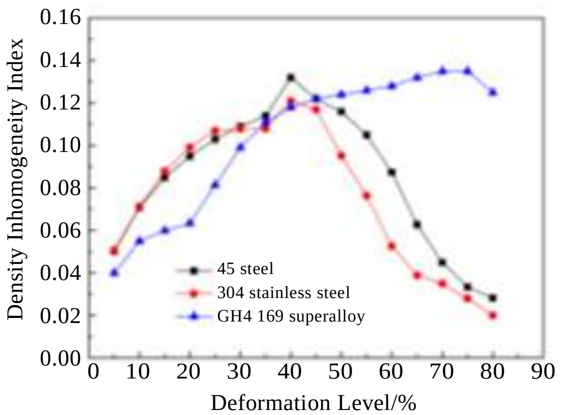

Fig.3 Relationship between density inhomogeneity and deformation level with different sheath materials

shows the density inhomogeneity index, D_{in}, in the present FEM results. It is observed that the inhomogeneity firstly increases gradually and then decreases with the increasing deformation. The D_{in} of billets encapsulated with 45 steel and 304 stainless steel start to decrease dramatically when the billets obtain 40% deformation, which indicates the density of billets becomes more homogeneous. However, the inhomogeneity lasts increasing except for the minor decrease at the end of the processing. In addition, when deformation level is lower than 40%, the billet encapsulated with GH4169 obtains the better homogeneity than others. However, its density homogeneity becomes worse when the deformation levels exceeds 40%. Finally, the value of density homogeneity achieved by the billet encapsulated is 0.02 for 304 stainless steel.

2.2 Effect of sheath materials on strain distribution

The effective strain reflects the accumulative deformation extent. It is generally recognized that the microstructure and mechanical performances of as-forged billet are affected by deformation degree. Fig.4 shows the effective strain distributions of billet encapsulated with different sheath materials on the cross-section of billet after processed by the canned forging. From the globe aspect, the strain distributions tends to present the shape of "U". This phenomenon is even more obvious in the billets covered with 304 stainless steel and GH4169. It is clearly noted that the strain in the center is higher than that positions remote from the center in the thickness direction. According to the same trend observed for the distribution of strain in the radial direction for all simulations, the higher strain concentrates in the middle plane with the increasing strength for sheath materials, which may be attributed to the expending area under triaxial compressive stress state. From the observation of strain distribution, nearly 30%, 50% and 90% areas exceed 1.5. Thus the results imply that the deformation compatibility between the P/M molybdenum of billet and sheath of GH4169 is better than other materials.

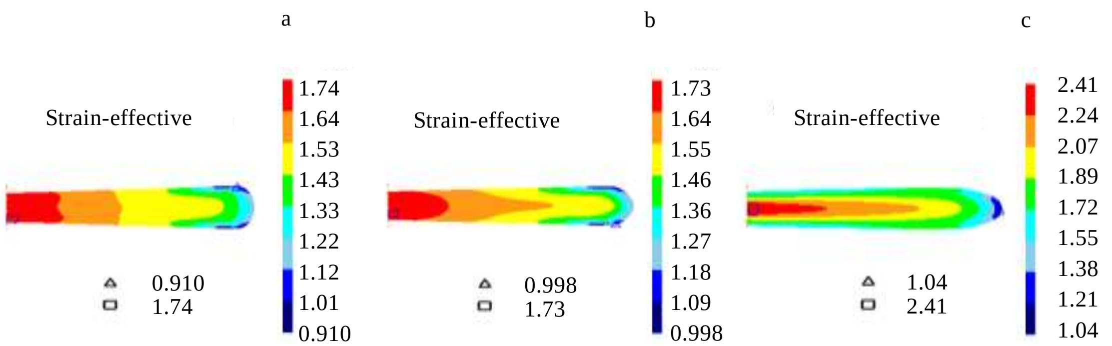

Fig.4 Distribution of effective strain with different sheath materials: (a) 45 steel, (b) 304 stainless steel, and (c) GH4169

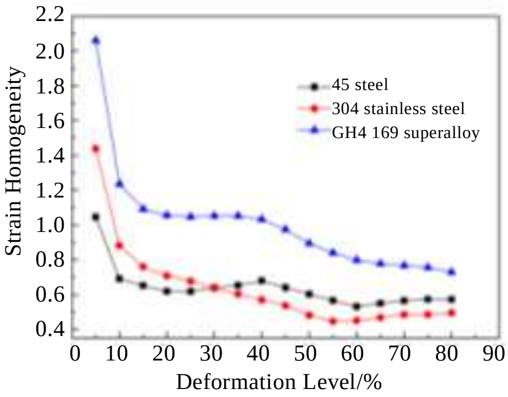

Fig.5 Relationship between strain inhomogeneity and deformation degree with different sheath materials

The strain inhomogeneity index, ε_{in}, is defined to analyze the effect of sheath materials on the strain homogeneity of billets qualitatively during processing. It is simply defined by the following formula.

$$\varepsilon_{in} = \frac{\varepsilon_{max} - \varepsilon_{min}}{\varepsilon_{avg}} \quad (2)$$

Where ε_{max}, ε_{min} and ε_{avg} are the maximum, minimum and average strain of the billet, respectively. Fig.5 shows the variation of the strain inhomogeneity with increasing deformation degree for different materials. It is apparent that all simulations present the similar tendency of strain inhomogeneity. That is the strain decreases dramatically firstly and tends to steady finally. However, the highest inhomogeneity is recognized in billet covered with GH4169 during the whole processing, which indicates the billet deforms uniformly. By contrast, the billet encapsulated with 304 stainless steel obtains the better homogeneity. Therefore, it is concluded that the strain inhomogeneity can be minimized by controlling the sheath materials.

2.3 Effect of sheath materials on average stress distribution

There is a compressive load imposed by the dies and a counter-stress generated by the sheath during canned forging processing. Thus it is reasonable that the plastic flow and densification can be improved due to the existing compressive state. Fig.6 shows the distributions of average stress of billets covered with different materials. It is observed that the billet stays in compressive state except for a small area near the edges for all simulations. The highest compressive stress is located in the centers of the billets, and it decreases linearly with the increasing distance from centers. This trend becomes more evident in Fig.6c. The reason is that the inner positions of the billets obtain the back-stress generated by the friction force.

Among the present simulations, the billet encapsulated with 304 stainless steel achieves the highest average stress, 81 MPa, as shown in Table 2. It is significant to note that there is no tension stress existing in billet covered with the

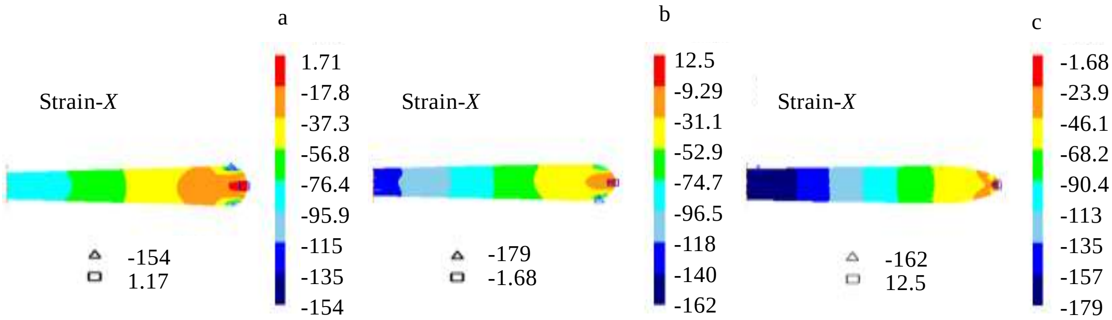

Fig.6 Distribution of mean stress with different sheath materials: (a) 45 steel, (b) 304 stainless steel, and (c) GH4169

Table 2 Average stress of the billet with different sheath materials

Sheath material	Percentage of tension stress/%	Average mean stress/MPa
45 steel	0.87	–51.8
304 stainless steel	0	–81.4
GH4169 superalloy	0.30	–80.3

304 stainless steel. The areas, which are in tension stress state, are prone to produce cracks. Comparing to the average stress, it can be concluded that the sheath of the 304 stainless steel is helpful to deformation and densification for billet of P/M molybdenum.

3 Conclusions

1) Finite element modeling is used to investigate the plastic deformation and densification for P/M molybdenum in isothermal canned forging. Separate simulation is performed using different sheath materials: 45 steel, 304 stainless steel and GH4169 superalloy.

2) The sheath of GH4169 greatly promotes the development of densification during processing. However, the good density homogeneity is obtained by billet which is covered with 304 stainless steel.

3) The distribution of strain presents the shape of "U" for all simulations, especially in the billet covered with GH4169. The strain increases with the increasing strength for sheath materials at the same levels of deformation. The strain homogeneity is the best in the billet with 304 stainless steel.

4) The average stress decreases linearly with the increasing distance from centers except for small area near the edges. The billet covered with 304 stainless steel is in full compressive stress state.

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不同包套材料对钼粉末锻造中塑性变形和致密化的研究

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摘　要: 采用有限元法来研究钼粉末等温包套锻造中的塑性变形和致密化。采用 3 种包套材料来进行模拟：45 钢、304 不锈钢、和 GH4169 合金。模拟表明，应变、密度和平均应力的分布明显受护套材料影响，应力、密度分布呈现“U”型。并且再相同锻造条件下，坯料的应力和密度随包套材料所受应力的增加而增加。当变形程度超过 40%时用 304 不锈钢材料做包套材料的坯料的均匀性最好。除了边缘的较小区域外，平均应力随着离中心的距离的增加而直线下降。研究表明，在这 3 种材料中，304 不锈钢最适合做钼粉末等温包套锻造的包套材料。

关键词: 钼粉末；包套锻造；护套材料；有限元法

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