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The finite-element study on extrusion of powder/solid composite clad rods

I-Nan Chou, Chinghua Hung*

Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta Hsuch Road, Hsinchu, Taiwan, ROC

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Abstract

This paper is concerned with the extrusion process of powder/metal composite clad rods. In this study, the finite-element model established in previous work was used to analyze the effects of various forming parameters, which included the extrusion ratio, the semi-die angle, the radius of the core and the material of the sleeve in extrusion processes. The finite-element results gave the consolidation condition, the stability of the powdered core and the maximum extrusion load for various forming parameters. Experiments were carried out, the results being in good agreement with the finite-element predictions. From the results of analysis, the effects of each forming parameter were determined. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Extrusion; Powder; Composite clad rods; Finite element; Forming parameters

1. Introduction

1.1. Extrusion of powder/solid composite clad rods

Rod materials with powder as the cores and metals as the sleeves are called powder/solid composite clad rods. This kind of composite is applied widely in superconductor wires, and dispersion-strengthened or fiber-reinforced composites. They have specific characteristics such as a high strength-to-weight ratio, better corrosion resistance, cryostatic stabilization for superconductors, and so on. In the case of superconductor wire-making, superconducting powder is set inside silver tubes as powder/solid composite clad rods. They are then made into coaxial wires by continuous extrusion processes (or drawing) to reduce the cross-sectional area of the composite clad rods and simultaneously consolidate the inner raw powder to a desirable density or strength before sintering processes. This composite extrusion process was named ‘‘powder in the tube’’, and has been applied extensively in superconductor wire-making.

Because the material properties of the powders and the metals are very different, non-uniform deformation sometimes will occur during the composite extrusion processes. A bad product caused by improper extrusion processes may contain defects and lose its special characteristics such as superconductivity. Therefore, it is very important for engineers to analyze the effects of working parameters and the deformation configuration of the materials during the extrusion processes.

1.2. A brief about this research

In the first part of this serial research, the deformation characterization of powder had been derived from the Drucker–Prager/Cap yield criterion with several material parameters [1]. In the present work of this research, the effects of forming parameters during the extrusion processes have been studied. First, the finite-element models built in previous research were used and modified in the present analysis. By taking various combinations of forming parameters, such as the semi-die angle, the extrusion ratio and the radius of the core, several extrusion cases were simulated individually. Secondly, some extrusion experiments were conducted to verify the results of the finite-element analysis. Finally, the results of the finite-element simulation were analyzed systematically, and the effects and importance of each parameter were discussed and concluded.

*Corresponding author. Tel.: 886-35-712121(55160); fax: 886-35-720634

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2. Literature review

2.1. Extrusion of solid composite clad rods

There have been many researches into solid composite clad rods in the past. An analysis was made by Avitzur [2] into choosing the proper combination of process variables to give homogeneous deformation of the core and sleeve for single-core billets. Zoerner [3] explored the hydrostatic extrusion of composite clad rods with hard cores and soft sleeves. He controlled various forming parameters such as the semi-die angles, the extrusion ratios and the interface bonding types, in order to determine the combination of working parameters for a good product and to find the forming limits for the prevention of defects. Osakada [4] used Cu–Al rods in his experiments into the deformation of composite material with a hard core during hydrostatic extrusion. He found that uniform deformation occured at lower extrusion ratios.

In respect of theoretical analysis, Avitzur [5] used the principle of the upper-bound theorem and the concept of minimum energy to determine the deformation types of composite clad rods during extrusion processes and then analyzed the forming limits by changing various forming parameters. On the other hand, the finite-element method has being used to simulate the complicated deformation patterns in composite extrusion recently, for example, the researches done by Song [6] and Park [7].

2.2. Extrusion of powder/solid composite clad rods

Only a few items of literature concerning the extrusion of powder/solid composite clad rods have been presented in the past. Oliver [8] mixed 99.9% Ni-powder and Ni–Al alloy-powder as the core, and used a 1040 steel-tube as the sleeve. He found that non-uniform deformation was caused by the critical hardening of the powder under high pressure during extrusion processes. Wang [9] used pure Al and Al_2O_3 powders as cores, and chose A6061 Al alloy as the sleeve. He concluded that the deformation of the workpiece was more unstable under a smaller extrusion ratio, caused by the inconsistent deformation of the core and sleeve in the relatively shorter die used.

Because of the very complicated deformation characteristics of the powder, there exist many difficulties in theoretical analysis at present. The material properties of the powder include compressibility, anisotropy, non-homogeneity, dependence between density-hardening and pressure, etc., which usually result in difficulties in modeling and numerical convergence. In previous research, the present authors obtained the material parameters of the specific yield criterion by experiment and successfully simulated extrusion processes. The finite-element analysis in this present advanced research was proceeded by using the previously verified finite-element model.

3. The finite-element analysis

3.1. Material properties and yield criterion of the powder

In this research, the superconductor YBCO ($YBa_2Cu_3O_x$) powder was chosen as the core of the composite clad rods. The characteristics of oxide family superconductor powders are similar to those of the granular materials, both exhibiting pressure-dependent yield and being significantly different in tensile and compressive yield strengths. The modified Drucker–Prager/Cap yield criterion [10] was chosen to model this superconductor powder. The options "cap plasticity" and "cap hardening" in software ABAQUS were used in the finite-element model. The main material parameters of the superconductor YBCO powder, such as friction angle, cohesion and the relationship of hydrostatic pressure and volumetric strain were obtained from direct shear tests and constrained compression tests [1].

In the finite-element analysis, the cohesion and the friction angle were assumed to remain at 18.8 kPa and 36.6°, respectively, during the extrusion processes. Furthermore, the relationship of hydrostatic pressure and volumetric strain was extrapolated by following an exponential curve in order to cover the ranges of extrusion pressure and compressive strain of the powder. In this research, both commercially pure copper and annealed A6061 aluminum alloy were chosen as the sleeves, their material properties being obtained from ASTM uniaxial tensile tests. The results of uniaxial tensile tests being shown in Fig. 1.

3.2. Boundary conditions and mesh system

An axisymmetric finite-element mesh system was constructed for the finite-element analysis. The powder was enveloped in the metallic tube, the front end of which was shaped to fit the profile of the die. The surfaces of the die and container were regarded as rigid and the coefficient of

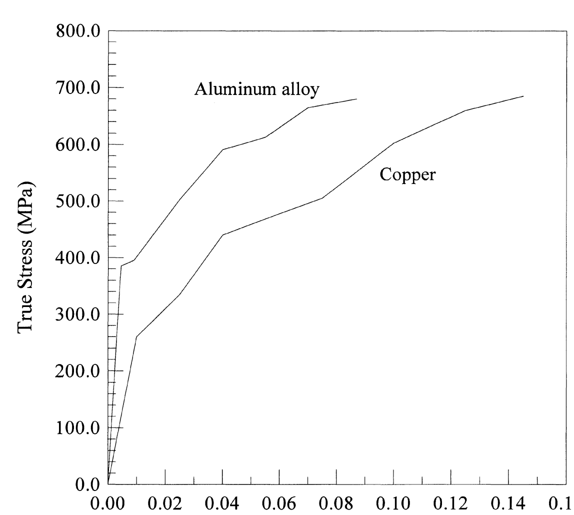

Fig. 1. True stress vs. true strain plot for copper and aluminum alloy.

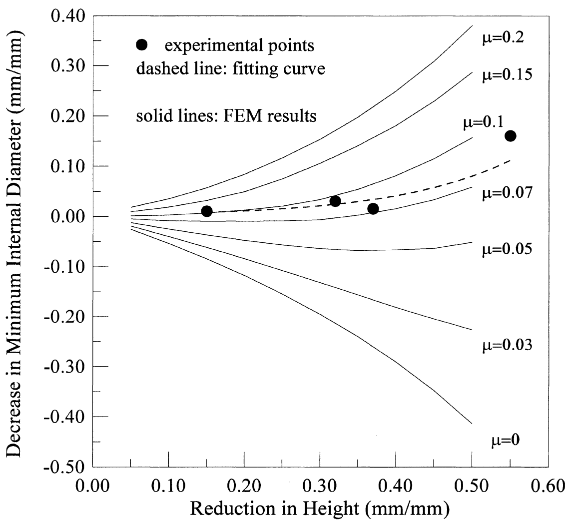

Fig. 2. The results of ring-compression tests.

friction between working surfaces was assumed to remain constant during the working process. Ring compression tests were conducted for determining the coefficient of friction (μ) when using lithium grease as the lubricant in the extrusion process. The results of the ring compression tests are shown in Fig. 2, the estimated value for the coefficient of friction being about 0.07.

For the present work, the bonding condition between the core and the sleeve was assumed to be sticky, i.e. the nodes on the boundary between the core and sleeve were shared by elements at both sides. For larger extrusion ratios, the meshes were divided finer in the axial direction to raise the aspect ratios of the elements. This could prevent numerical errors caused by elements that were too long and thin at the later stage of extrusion simulation.

3.3. Forming parameters

In this research, the extrusion ratio, the radius of the core, the semi-die angle and the material of the sleeve were chosen to be the controlled forming parameters. The diameter of the billet was fixed at 13.5 mm. By varying combinations of working parameters, this simulation aimed at determining their influence on the powder/metal flow, the density distribution of the powder and the extrusion load.The selected values of parameters are summarized as follows: (1) the extrusion ratio (r): 1.4446, 2.5682 and 5.1653; (2) the radius of core (R_c): 3.0, 3.5 and 4.0 mm; (3) the semi-die angle (α): 10–30° (interval: 5°); (4) the chosen sleeve material: commercially pure copper and annealed A6061 aluminum alloy.

4. Experiments

In order to verify the results of the finite-element simulation, designed experiments with the same working parameters were conducted. SKD61 and tungsten carbide were used as the material of die and the extrusion ram, respectively, their dimensions being identical to those of the simulation. The extrusion apparatus was set up with in a universal testing machine having a maximum load of 30 tons.

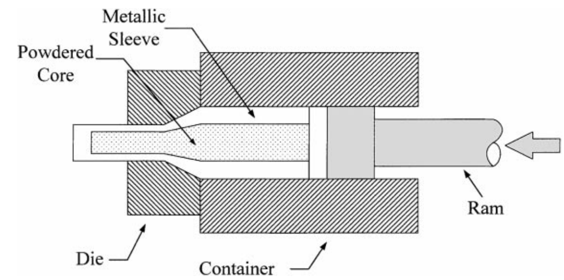

Fig. 3. The extrusion of composite clad rods.

The extrusion billet consisted of the powder and metallic tube. A6061 aluminum and copper bars were formed into one-side opening tubes and then heat treated by fully annealing to make them softer and more homogeneous. The initial filling density of superconductor YBCO powder was kept at 2.5 g/cm^3 for each case, being known to be a suitable value from previous studies. Fig. 3 illustrates the arrangement of the composite extrusion experiment. The controlled forming parameters were the same as those in the simulation, but only a portion of the whole number of cases was conducted.

5. Results and discussion

5.1. The deformed configurations

Compared to those of solid clad rods, the deformed configurations of powder/solid clad rods are more complicated. At the start of extrusion process, the billet would be shortened and the powder consolidated heavily because of its compressibility. The powder then becomes increasingly harder so that the flow of the materials would be in a poor condition: photographs of typical profiles of extruded clad rods are shown in Fig. 4.

The deformed configurations of the extruded workpieces can represent the powder/metal flow during the working process. Three typical deformed configurations for various extrusion ratios are shown in Fig. 5. The case with an extrusion ratio of 1.44 shows that there is large shearing action on the boundary between the core and sleeve. The flow velocity of the sleeve is faster than that of the core, and the flow is becoming impeded at the center of the core. However, the results are completely different from those of the cases with extrusion ratios 2.57 and 5.17. Under higher extrusion ratios, the powder shows uniform deformation without much shearing and the sleeve displays only a little shear deformation which may be caused by the friction between the rigid die and billet. The flow velocity at the center of clad rod is fastest, becoming slower when close to the contact interface.

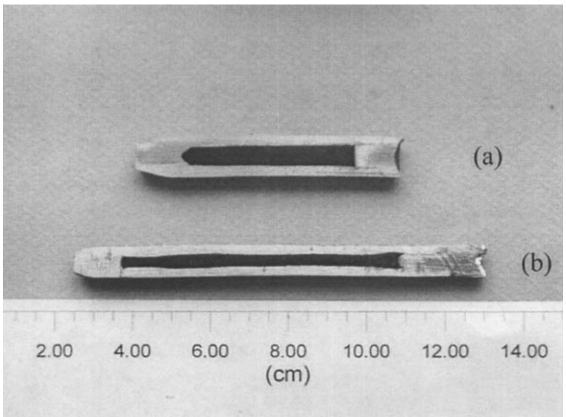

Fig. 4. The cross-sectional view of extruded clad rods for extrusion ratios of (a) 1.44; and (b) 2.57.

5.2. The effects of extrusion ratios

5.2.1. The consolidation condition of the powder

A good consolidation condition includes both a high-consolidated density and a uniform distribution of the powder. Fig. 6 shows the typical contours of PEEQ, which indicate the hydrostatic pressure in the cap plasticity model. In the definition of the Drucker–Prager/Cap model, the hydrostatic pressure is dependent directly on the volumetric strain (density). Therefore, in these contour plots, a larger value of PEEQ means a higher density. To obtain the exact value of the powder density, the volumetric strains of the elements can be calculated for each axial location. The density distributions of extruded powder for various extrusion ratios with $R_c = 3.5$ mm, $\alpha = 15^\circ$ are shown in Fig. 7. In the cases with an extrusion ratio 1.44, the density at the rear piece of the extruded powders was greater than those at the front piece. However, the density distribution with an extrusion ratio of 2.57 is more uniform than that with an extrusion ratio of 1.44. For a higher extrusion ratio, 5.17, the variation of density in the axial direction is almost negligible.

It is predictable that a high extrusion ratio will result in a highly consolidated density of the powdered core. In Fig. 7, it can be found that the difference between the density curves for extrusion ratios of 1.44 and 2.57 is much larger than that between extrusion ratios of 2.57 and 5.17. This results from a critical condition of the powder density, as the compressible volume between the powder particles is becoming smaller with increased extrusion ratio. Conclusively, the effect of the extrusion ratios on the consolidation of the powder is very obvious.

5.2.2. The stability of core and maximum extrusion load

The value of R_cf/R_sf can represent both the volume fraction of the powdered core and the stability of the extruded product. Here R_cf and R_sf are the radii of the core and the sleeve after extrusion, respectively. The value of R_cf/R_sf is another good means of comparison between the results of the finite-element simulation and the experimental results. From experiments, some values of R_cf/R_sf were measured at the middle section of an extruded rod, and then their average taken. The values of R_cf/R_sf for the simulation and experiments with various extrusion ratios are plotted in Fig. 8, from which it is seen that a higher extrusion ratio results in a little smaller value of R_cf/R_sf. Fig. 9 shows that a greater extrusion ratio results in better stability of the volume fraction of the extruded rods.

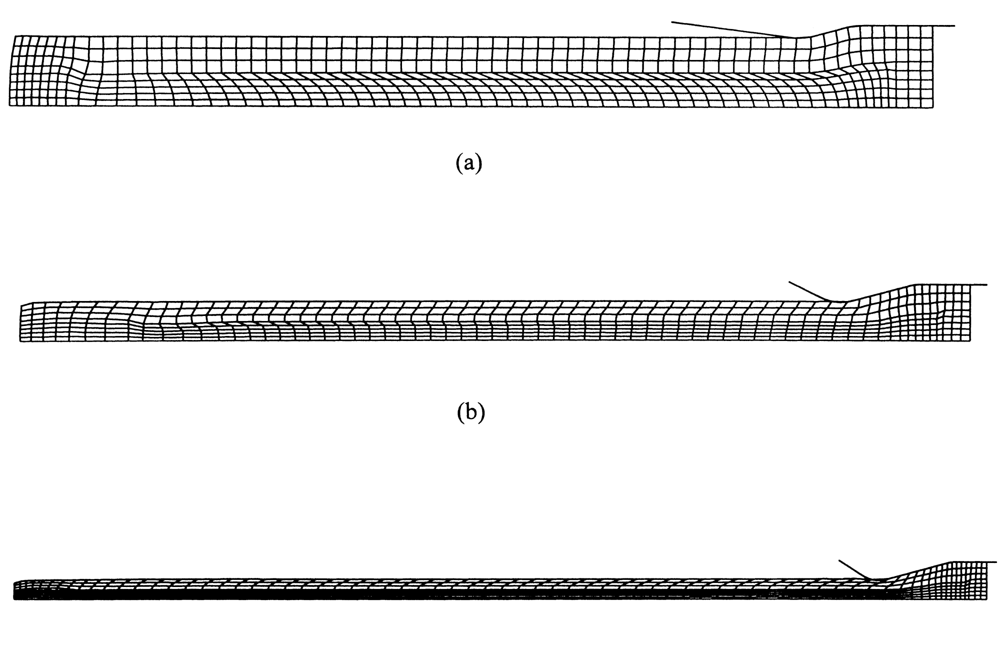

Fig. 5. The deformed configurations for various extrusion ratio: (a) 1.44; (b) 2.57; and (c) 5.17.

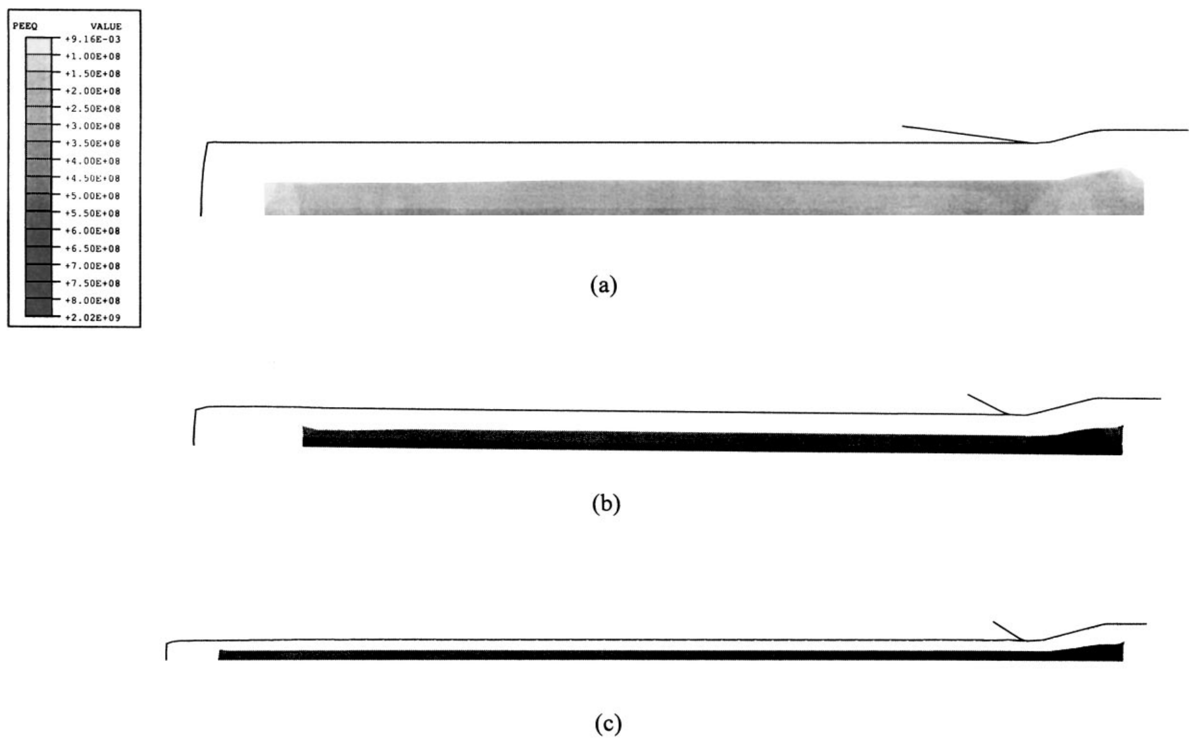

Fig. 6. The contour plots of hydrostatic pressure for various extrusion ratios: (a)1.44; (b) 2.57; and (c) 5.17.

The maximum extrusion load is another important consideration to manufacturers. In general, a greater extrusion ratio will result in a greater extrusion load. Fig. 10 shows the effect of the extrusion ratio on the maximum extrusion load. The experimental data for an extrusion ratio of 5.17 is absent because the maximum extrusion load had exceeded 30 tons, which is the loading limit of the present extrusion apparatus; however, the rest of the experimental points are in agreement with the results from the finite-element simulation.

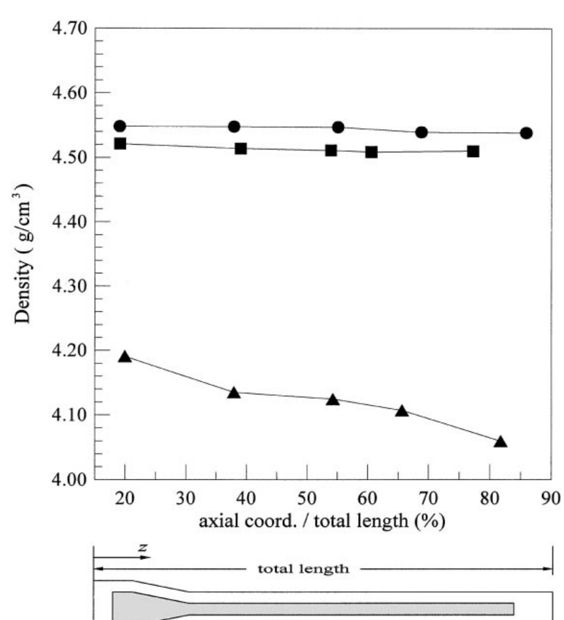

Fig. 7. The density distribution of the extruded powder for extrusion ratios of: round points 5.17; square points 2.57; triangular points 1.44.

5.3. The effects of semi-die angles

5.3.1. The consolidation condition of the powder

With the same extrusion ratio ($r = 2.57$) and radius of core ($R_c = 3.5$ mm), the density distributions of the extruded

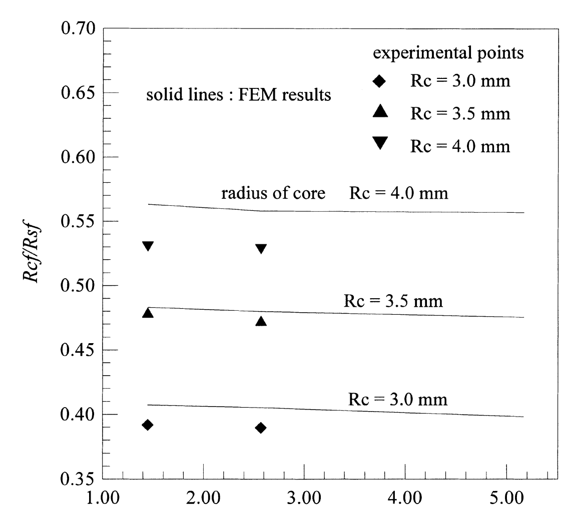

Fig. 8. The variation of R_cf/R_sf with extrusion ratio.

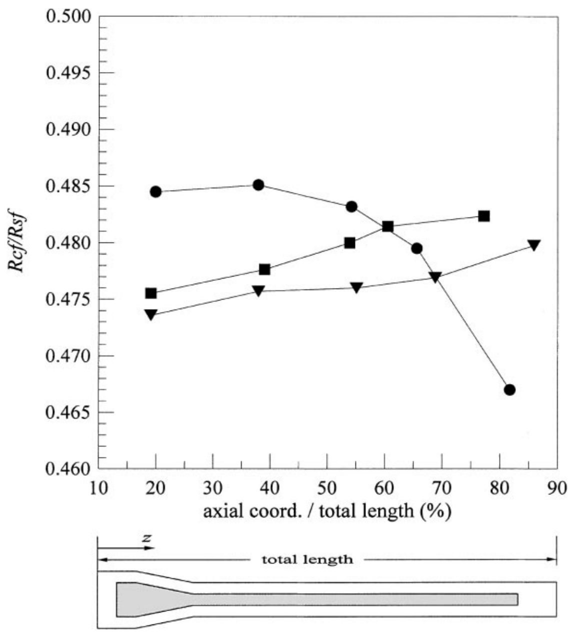

Fig. 9. The distribution of R_cf/R_sf for the extruded powder for extrusion ratios of: round points 1.44; square points 2.57; triangular points 5.17.

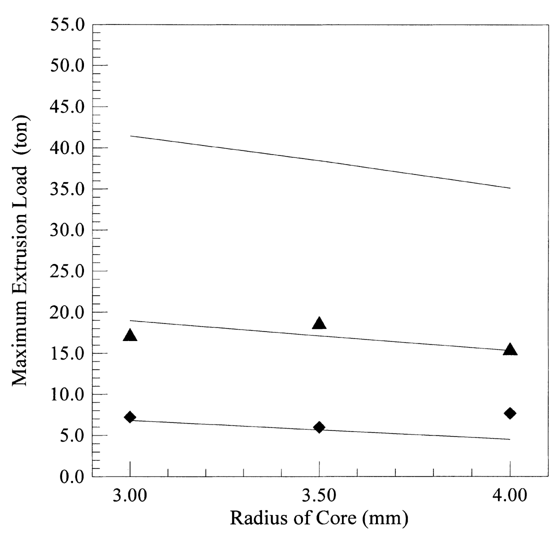

Fig. 10. The variation of maximum extrusion load with radius of core for extrusion ratios of: diamond points 1.44; triangular points 2.57. The solid lines are FEM results, the top line being for an extrusion ratio of 5.17, having no equivalent experimental results.

powder with respect to three semi-die angles are shown in Fig. 11. The density distribution with a semi-die angle 10° is very uniform because the deformation region is sufficiently long. The cases with larger angles are not so uniform: however, the variations of density are only about $0.02 \sim 0.06$ g/cm^3. It can be concluded that the semi-die angle has only a weak effect on the consolidation condition of the powder.

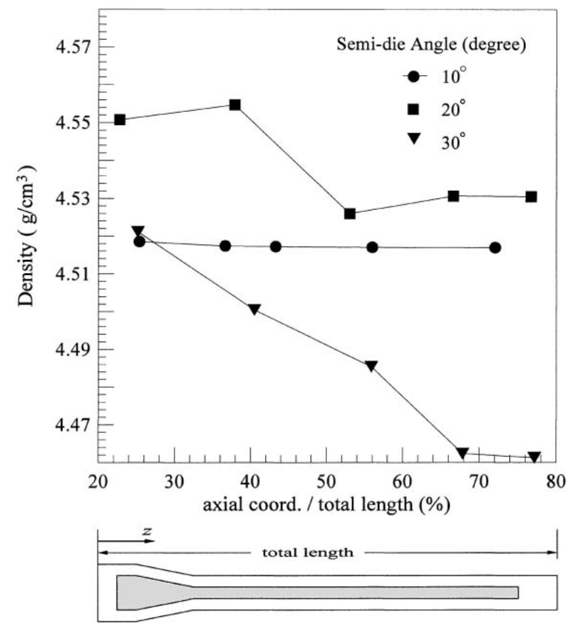

Fig. 11. The density distribution of extruded powder with various semi-die angles.

5.3.2. *The stability of the core and the maximum extrusion load*

The variation of R_cf/R_sf along extruded rods with different semi-die angles is displayed in Fig. 12. The case with a small semi-die angle has a stable volume ratio of composite clad rod. Cases with larger semi-die angles display a peak value of R_cf/R_sf at the middle section of the extruded rod. From the results of density distribution and values of R_cf/R_sf, it can be concluded that the powder rapidly run backwards in quantity

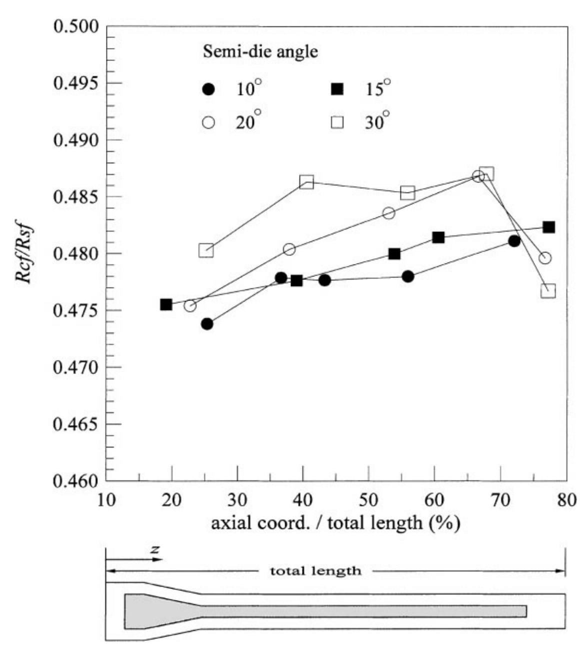

Fig. 12. The R_cf/R_sf distribution with various semi-die angles.

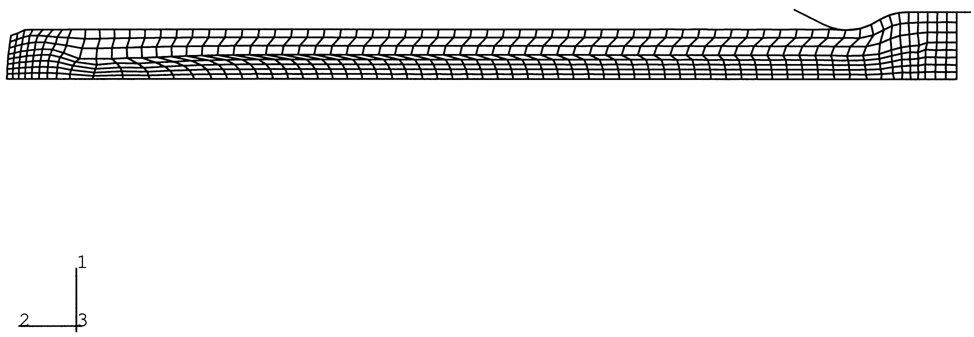

Fig. 13. The shearing on the boundary between the core and the sleeve for a semi-die angle of 30°.

at the beginning of extrusion because of the higher die pressure resulting from a larger die angle. In the deformed configuration for a semi-die angle of 30°, shearing is very obvious on the boundary between the core and sleeve at the front end of the extruded rod (see Fig. 13).

The semi-die angles had a strong effect on the maximum extrusion load. As shown in Fig. 14, the maximum extrusion load decreases with a increasing semi-die angle from 10° to 30° for an extrusion ratio of 2.57 and this was verified by the experimental results. These results, however, are completely opposite to those for cases with an extrusion ratio of 1.44. In fact, a complicated relationship between extrusion load and die angles also exists in the extrusion (or drawing) of solid rods [11]. In conclusion, the maximum extrusion load is related strongly to the length of the die, especially when friction is not negligible.

5.4. The effects of core radii

The variation of powder density with the initial radius of core is shown in Fig. 15. Because there is more compressible volume in a larger powdered core, the density can not be consolidated as well as in a smaller core within the same

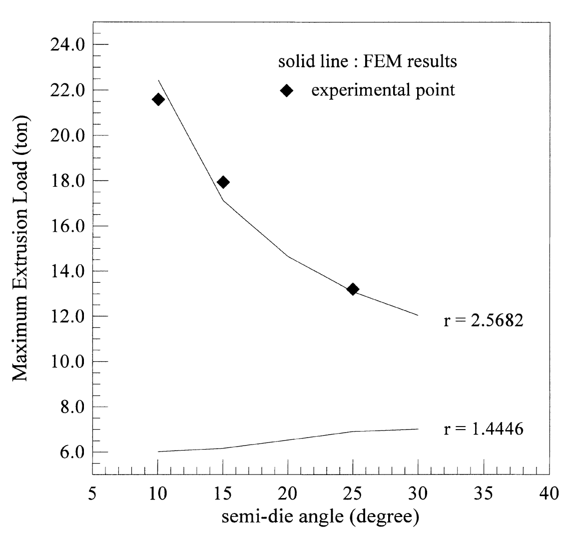

Fig. 14. Maximum extrusion load vs. semi-die angles.

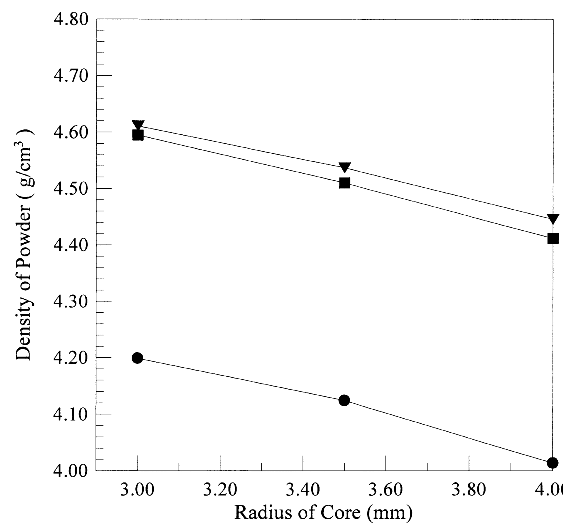

Fig. 15. The density at the middle section of the extruded core for various radii of core for extrusion ratios of: round points 1.44; square points 2.57; triangular points 5.17.

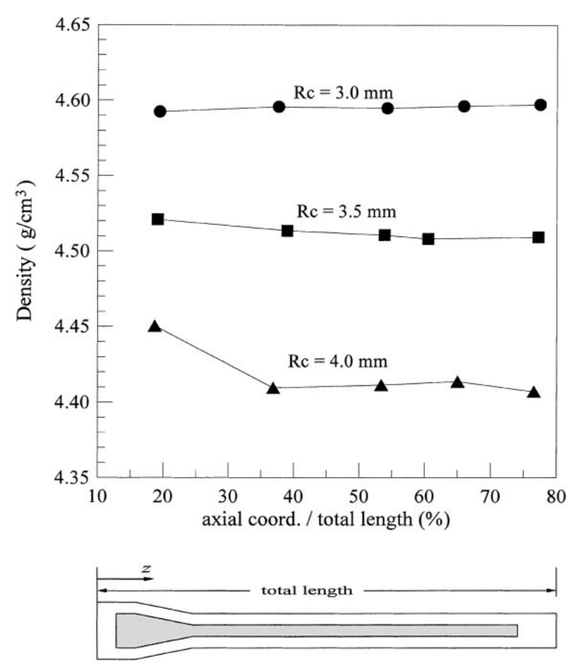

Fig. 16. The density distribution with various radii of core.

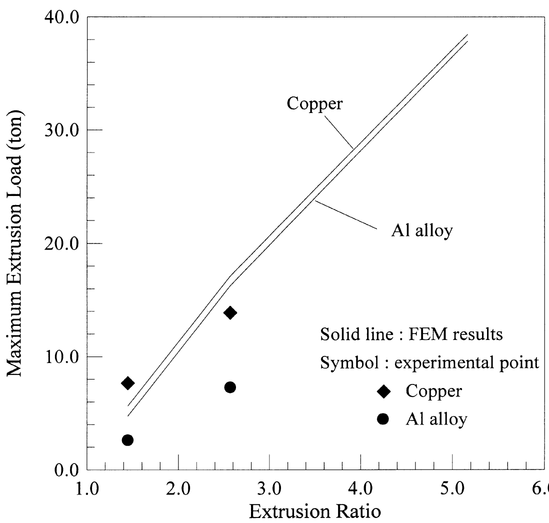

Fig. 17. The comparison of maximum extrusion load when using copper and aluminum alloy as sleeves.

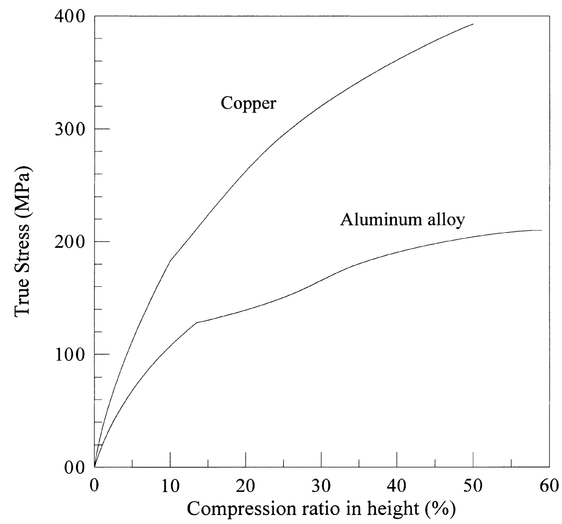

Fig. 18. The results of compression tests for copper and aluminum alloy.

extrusion die. In Fig. 16, the density distribution of the powdered core is most uniform under the condition of $R_c = 3.0$ mm. For the value of R_cf/R_sf, it is very natural that a larger radius of core will result in a higher value (see Fig. 8). However, difference between cases on the distribution of R_cf/R_sf with various radius is not evident. With a better consolidation condition, a smaller radius of core always results in a higher maximum extrusion load (see Fig. 10).

5.5. The effects of aluminum alloy sleeve

The cases in the above sections were carried out using commercially pure copper as the sleeve. When another kind of sleeve material, A6061 aluminum alloy, was used in the simulation and experiments for extrusion, the consolidation density was a little lower than that with the copper sleeve. As shown in Fig. 17, the maximum extrusion load for copper is higher than that for aluminum alloy even though the aluminum alloy is stronger than the copper in tension. This may result from the greater strain-hardening effect of copper. For verifying this conclusion, simulations on solid rods extrusion for these two materials were conducted, the results also showing that the maximum extrusion load for copper greater.

Despite the strain-hardening effect, there still exists some difference between the results from experiments and those from finite-element simulation when using different sleeve materials. This could result from the Bauschinger effect for both kinds of metals. To verify this assumption, a simple compression test was conducted with a cylindrical billets having an aspect ratio (diameter to height) of 1.0. The results of compression tests (Fig. 18) for the materials show that the aluminum alloy is indeed softer than the copper in compression, which is completely opposite to the results of uniaxial tensile tests (in Fig. 1). Because compressive stresses are dominant during the extrusion process, the maximum extrusion loads for the cases with an aluminum alloy sleeve are smaller than the simulated values obtained by using standard tensile-test data as the material properties. Nevertheless, the effect of the sleeve metal is not very significant.

5.6. Discussion

After the analysis with several extrusion forming parameters, it was found that these parameters have complicated influences on the extrusion process and the products. The deformed configurations from the finite-element simulation show that the extrusion ratio and semi-die angle are the most important factors affecting the velocity field, and that a shorter die can not provide sufficient length for the powder to flow uniformly with the sleeve metal. A larger extrusion ratio (Fig. 5(c)) can result in a velocity field similar to that in the extrusion of solid rods, i.e. with little shearing and being more stable. The velocity field could also be used to indicate whether the consolidation condition is good or not.

From the above results, the relationship between these extrusion forming parameters and their effects on extrusion products can be summarized in Table 1.

For obtaining a highly consolidated and uniformly distributed density of powder, a large extrusion ratio and a small radius of core are more effective in the extrusion

Table 1
The effects of the extrusion forming parameters on the products

Effect	Parameter		
	Extrusion ratio (r)	Semi-die angle (α)	Core radius (R_c)
Consolidated density	High	Low	Medium
Density distribution	High	Low	Medium
Stability of core	High	Medium	Low
Maximum extrusion load	High	Medium	Medium

processes. A small and proper semi-die angle can also help in the uniformity and consolidation of the powder but its effect is not very significant. The choice of sleeve material is another factor to be considered. If the sleeve metal is sufficiently enough and ductile, the consolidation effect will be a little better. As for the stability of the volume fraction (R_cf/R_sf) of the powder, a sufficiently large extrusion ratio and a small semi-die angle are necessary.

With regard to economic considerations, a lower maximum extrusion load is often preferred. In general, the maximum extrusion load is related directly to the die profile. The extrusion ratio is surely the most important factor in respect of the extrusion load, but the consolidated density is not linearly proportional to the extrusion ratio. A large extrusion ratio always results in a very high extrusion load, but the powdered core may not be consolidated as much because of the limit of the critical density of the powder. Moreover, a very high extrusion load will magnify the effect of friction and degrade the surface condition of the products. For another parameter of the die profile, the semi-die angle, a large value combined with a high extrusion ratio can also reduce the maximum extrusion load, but the condition for density distribution and stability of the core are becoming poor at the same time. It is worthwhile to use optimization method to reduce the maximum extrusion load by including the die profile with another forming parameters, such as the radius of the core and the material of the sleeve, as the design variables.

6. Conclusions

The effects of extrusion forming parameters had been obtained by finite-element simulation and experiment. From the results,the following can be concluded.

1. The extrusion ratio is a very important factor in the extrusion of powder/solid clad rod. A better product can be obtained if a higher extrusion ratio is used; however, the maximum extrusion load will be higher at the same time.
2. The semi-die angle is not only a helpful parameter on the stability of core, but is also an important factor on the maximum extrusion load. The choice of semi-die angle will be determined by the objectives of manufacture.
3. A smaller radius of core could result in a better consolidation condition and a stable powdered core.
4. The effect of the sleeve material is not significant, but metal with good ductility in compression is still regarded as a better choice for the consolidation condition.

From the above conclusions of each forming parameter, the optimum design of die profile is necessary in order to obtain a better consolidation condition and to reduce the extrusion load simultaneously. In addition to optimum design of die profile, another possible improvement is to extrude powder/solid composite clad rods with hydrostatic extrusion apparatus. According to preliminary experiments, using the hydrostatic extrusion technique not only reduces the extrusion load, but also increases the stability of core and improves the surface condition of the clad rod at the same time. The hydrostatic extrusion process will be the focus in the future research of the present authors into the extrusion of powder/solid composite clad rods.

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