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Semi-solid extrusion of TiC_p/2024Al composites prepared by contact reaction method①

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Abstract: The contact reaction method was employed to prepare TiC_p/2024Al composites and the semi-solid extrusion was employed to manufacture composite rods. Through many experiments, suitable processing parameters were obtained, under which sound rods can be fabricated. It is found from the extrusion pressure —stroke curves of semi-solid extrusion that the deformation force during semi-solid extrusion is low and steady. The reason for lower extrusion pressure of semi-solid extrusion was given. Some fabrication defects, such as break-out and excessive extrusion force, owing to the inappropriate selection of processing parameters were also observed. The microstructures of TiCp/2024Al composites are characterized by well-densified matrix, uniformly distributed TiC particles, some banded particle clusters and realignment of TiC particles along the extrusion direction, and no fracture of TiC particles. The mechanical properties of TiC_p/2024Al composites are much higher than those of unreinforced alloy. In the meantime, the elongations of the composites are maintained at the level enough for practical applications.

Key words: TiC_p/2024Al; semi-solid extrusion; microstructure; mechanical properties **Document code:** A

1 INTRODUCTION

Because of their high specific strengths, specific moduli, wear resistance and thermal stability, the Al-based composites reinforced by ceramic particles have attracted much interest in the development of manufacturing processes for such composites. The fabrication processes of ceramic particles reinforced aluminum alloy composites by casting techniques such as squeeze casting, compocasting, stirring method and die casting process are very promising for manufacturing composite parts at relatively low cost[1]. However, in the above mentioned methods, the reinforcing particles are directly incorporated into liquid matrix, thus the morphology of reinforcements is not easily controlled and the reactants often appear at the interface between matrix and reinforcement, which deleteriously affects the mechanical properties of final composites[2]. Compared to the above methods, the Contact Reaction Method(CRM), invented by Harbin Institute of Technology of China, being an improvement of XD™ method, has many advantages. The procedures for fabricating TiC_p/2024Al composites with CRM are as follows: elemental powder + alloy powder → mechanical mixing → cold pressing $\xrightarrow{\text{preform}}$ melting in alloy liquid → pouring → composite ingot casting. As far as the CRM is concerned, the reinforcing particles are formed within the matrix, the size of reinforcements is relatively small, with about 1 μm in diameter, the shape of reinforcements is nearly spherical, and the interface is clean. These are of benefits to the mechanical properties of final composites[3].

To make particle reinforced aluminum alloy composites be widely applied in industrial departments, they will inevitably be subjected to plastic forming, especially to extrusion. The fracture of particles during cold and hot extrusion has been extensively observed[4]. Compared to solid extrusion, the extrusion of metals in the semi-solid state needs lower deformation force. Especially for particulate reinforced aluminum alloy composites, the deformation force of semi-solid extrusion is much lower than that of solid extrusion[5~7]. Therefore, a semi-solid extrusion experiment of TiC_p/2024Al composites fabricated by the CRM was carried out in the present study to manufacture MMCs rods without defects such as fracture of particles. Additionally, the possibility of rod fabrication for semi-solid extrusion was investigated for TiC_p/2024Al composites fabricated by the CRM. The microstructure and mechanical properties of the composite rods were also investigated.

2 EXPERIMENTAL

The matrix alloy used in the experiment was 2024Al alloy. The TiC_p/2024Al composites were prepared by the CRM. The volume fractions of TiC particles are 2.5%, 5%, 10% and 15%, respectively. The TiC_p/2024Al composite slurry was obtained by remelting the ingot castings in a vacuum furnace. A semi-solid extrusion process for TiC_p/2024Al compos-

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ites includes three steps: 1) the composite slurry is poured into the preheated extrusion container; 2) the pressure is imposed on composite slurry by hydraulic press; 3) the partially solidified composites in the deformation zone are extruded out from the die exit. Fig.1 shows the semi-solid extrusion equipment for the fabrication of MMCs rods. The punch velocity was controlled by hydraulic press. The specifications of experimental equipment for semi-solid extrusion of composite slurry are shown in Table 1. During the semi-solid extrusion, the preheating temperature of the container and die were 400 ℃ and 200 ℃, respectively, the pouring temperature of composite slurry was about 80 ~ 100 ℃ above the liquidus of the matrix alloy, and the punch velocities were 1.0, 3.0 and 5.0 mm/s, respectively. To investigate the possibility of the fabrication of MMCs rods by semi-solid extrusion, the extrusion pressure—stroke curves for extrusion under conditions of various punch velocities were recorded by X-Y recorder.

3 RESULTS AND DISCUSSION

3.1 Deformation force

Table 1 Specifications of experimental equipment

Container		Die	
Diameter / mm	Height / mm	Angle / (°)	Diameter / mm
40	80	45	12

When the punch velocity was 3.0 mm/s, the semi-solid extrusion process can reach the stable state, sound composite rods can also be manufactured successfully, and the extrusion pressure—stroke curves for semi-solid extrusion of TiC_p/2024Al composites with various volume fractions of TiC particles were recorded, as shown in Fig.2(a). It can be seen that the extrusion pressure of the stable semi-solid extrusion process is almost constant and very low due to the low yield strength of partially solidified composites in the deformation zone during the stable semi-solid extrusion process. As shown in Fig.3(a), during the stable semi-solid extrusion process, the materials in the container will be partially solidified. And the temperature of semi-solid composites will be high. According to the theory proposed by Sellars et al[8], the relationship between the yield strength of material and the strain rate at high temperatures can be

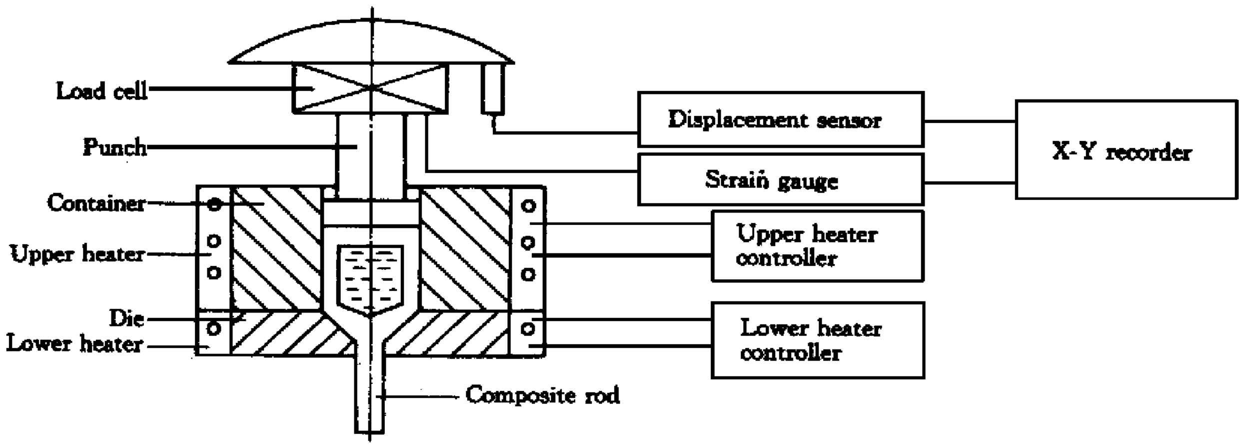

Fig.1 Schematic diagram of semi-solid extrusion experimental apparatus for fabrication of metal matrix composite rods

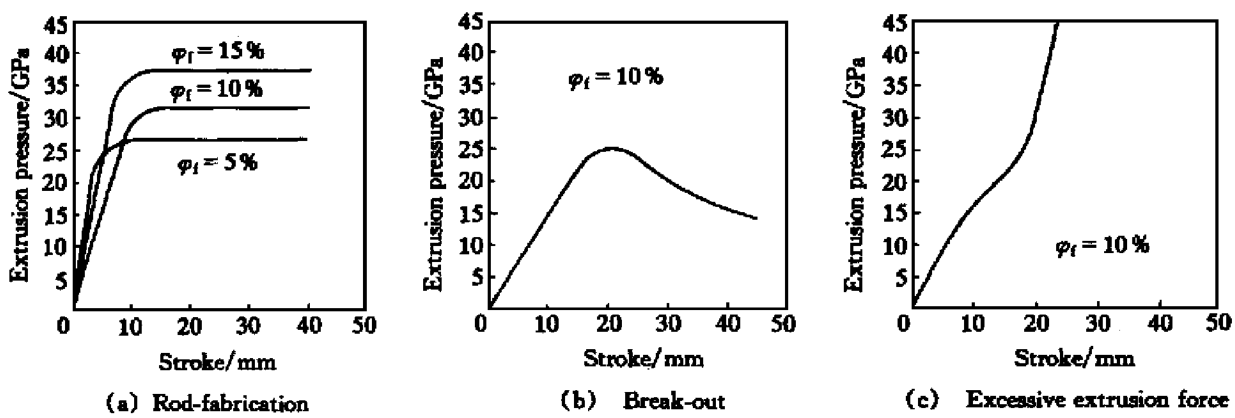

Fig.2 Extrusion pressure—stroke curves of TiC_p/2024Al composites containing 5%, 10% and 15% volume fractions of TiC particles for semi-solid extrusion

(a) —Rod fabrication; (b) —Break-out; (c) —Excessive extrusion force

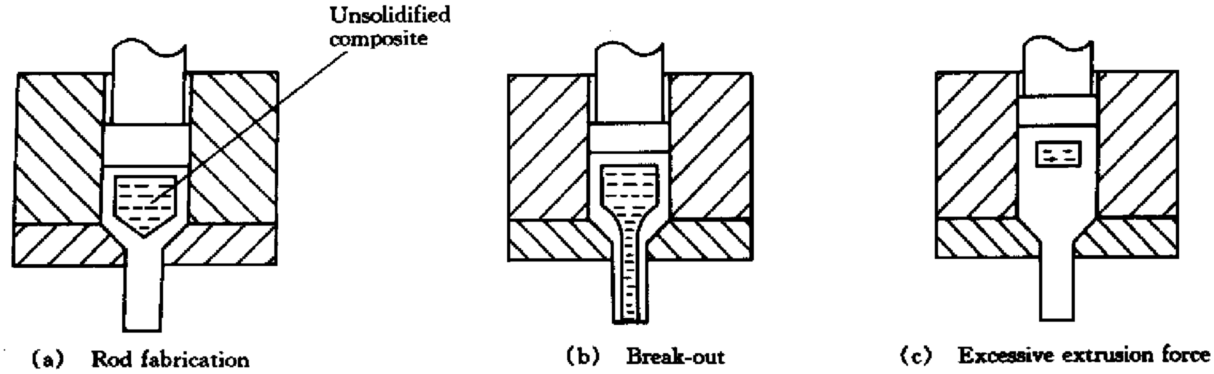

Fig.3 Fabrication possibility and defect types
(a) —Rod fabrication; (b) —Break-out; (c) —Excessive extrusion force

obtained as follows:

$$[\sinh(\beta\sigma_0)]^{\delta} = (\bar{\dot{\varepsilon}}/B)\exp(Q/RT) \quad (1)$$

where δ, β and B are material constants, σ_0 is the yield strength of material at high temperatures, $\bar{\dot{\varepsilon}}$ is the average strain rate, Q is the activation energy for deformation, R is the universal gas constant, and T is the temperature. For most materials, the above hyperbolic sine model can be simplified further as follows[9]:

$$\sigma_0 = \exp\{[\ln(\bar{\dot{\varepsilon}}/B) + Q/RT]/\delta\}/\beta \quad (2)$$

For cylindrical extrusion process, the strain rate can be approximately determined using the following equation[10]:

$$\bar{\dot{\varepsilon}} \approx \frac{v}{h}\ln\lambda \quad (3)$$

where v is the extrusion velocity, h is the effective height of extrusion specimen, and λ is the extrusion ratio. In the present study, v is 3.0 mm/s, h is 60 mm and λ is about 11∶1. So $\bar{\dot{\varepsilon}}$ is about 0.12 s^{-1}. When the material constants were selected for the case of Al alloy (β = 0.031 1 MPa^{-1}, δ = 5.0 MPa^{-1}, $B = 8.02 \times 10^{11}$ s)[8,11], the curve of σ_0 vs T can be obtained according to Eqn.(2), as shown in Fig.4.

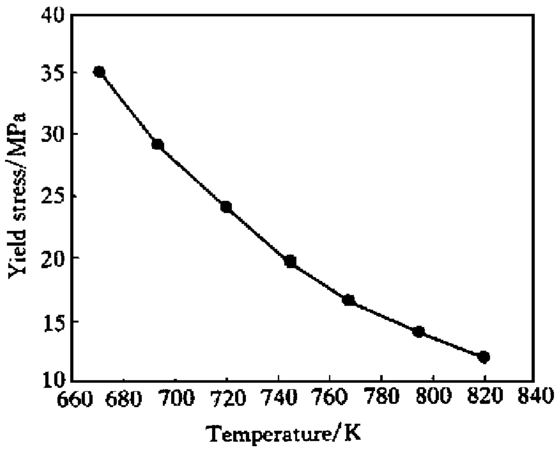

Fig.4 Relationship between yield strength of material and temperature in high temperature range

From Fig.4, it can be seen that at the high temperatures ranging from 660 K to 820 K, the yield strength of the aluminum alloy will rapidly decrease with the increase in temperature. So from the foregoing discussion, it can be concluded that the extrusion pressure of semi-solid material will be much lower than that of solid material. It can also be seen from Fig.2(a) that for various volume fractions of TiC particles, the extrusion pressure will be different and the pressure will increase with the increase in volume fraction of TiC particles. When aluminum alloy reinforced by TiC particles is in semi-solid state, most TiC particles will exist at the liquid grain boundaries and the solid matrix is almost free of TiC particles[3]. When the mixed materials of solid matrix and liquid grain boundaries with TiC particles are subject to extrusion, the whole deformation process will consist of two parts: the plastic deformation of solid matrix and the flow of liquid grain boundaries with TiC particles. So the extrusion pressure σ_T can be divided into two parts: the flow stress σ_s of solid matrix and the pressure p of liquid grain boundaries, as shown in the following equation[9]:

$$\sigma_T = \sigma_s + f_l p \quad (4)$$

where f_l is the liquid volume fraction. For the same temperature, liquid flow velocity and liquid volume fraction, σ_s is the same but p is different due to various liquid viscosities. For the semi-solid cylindrical extrusion process, the maximum liquid pressure will be[12]

$$P_{l\max} = \frac{\mu u h}{2K} \quad (5)$$

where μ is the viscosity of liquid, u is the liquid flow velocity, h is the height of extrusion specimen, and K is the permeability. From Eqn.(5), it can be seen that the pressure in liquid will increase with the increase in liquid viscosity for the same liquid flow velocity. Due to the addition of TiC particles in the liquid, the viscosity of liquid matrix alloy will increase. The larger the amount of TiC particles is, the larger the viscosity of liquid matrix is[13].

When the punch velocity was 5.0 mm/s, break-out phenomenon was observed. Compared with the solidification speed of composite slurry in the container, the punch velocity of 5.0 mm/s is so fast that the liquid composites in deformation zone are extruded out from the die, as shown in Fig.3(b). At the same time the extrusion pressure dramatically decreases, as shown in Fig.2(b). When the punch velocity is 1.0 mm/s, the MMCs rod fabrication is impossible because the punch velocity of 1.0 mm/s is so slow compared with the solidification speed of composite slurry that the whole composite in the deformation zone is fully solidified and the temperature is relatively low, as shown in Fig.3(c). Under this condition, the excessive extrusion pressure is needed, as shown in Fig.2(c), and the extrusion process is equivalent to the solid extrusion.

3.2 Microstructures and mechanical properties

Fig.5 shows the microstructures of semi-solid extruded composites with 0.05 and 0.10 volume fractions of TiC particles after T6 treatment along the directions perpendicular to and parallel to the extrusion direction. The uniform distribution and dispersion of TiC particles in the matrix are observed from Fig.5, and banding and reorientation of TiC particles along the extrusion direction are also evident. Naturally, the fracture of particles often occurs during cold and hot extrusion due to the localization of strain, particle size, particle aspect ratio and volume fraction. Among these factors, the local stress (related to imposed strain), particle size and aspect ratio of particles play the most important roles. The higher the local stress in the matrix acting on the particles and the larger the size and aspect ratio of particles, the easier the fracture of particles during extrusion is[4,14]. Therefore, no observation of the fracture of particles in Fig.5 is mainly due to the following factors: lower local stress acting on the particles by matrix during semi-solid extrusion than that during hot and cold extrusion; small size of TiC particles with about 1 μm diameter; the aspect ratio of TiC particle close to 1.

The elastic modulus, ultimate tensile strength, yield strength and elongation of composite rods along the extrusion direction are shown in Fig.6. The strength of the composite rods after T6 treatment increases with the increase in volume fraction of TiC particles and is much higher than that of 2024 Al alloy after T6 treatment. This is mainly due to following factors: the dispersion strengthening of fine TiC particles in the matrix; the refinement of the primary grains by crystallization and the elimination of the microvoids in the matrix under hydrostatic pressure and flow solidification; the further breaking up of primary grains by extrusion deformation; the realignment of the TiC particles in the matrix by plastic flow and the good densification of the matrix under extrusion

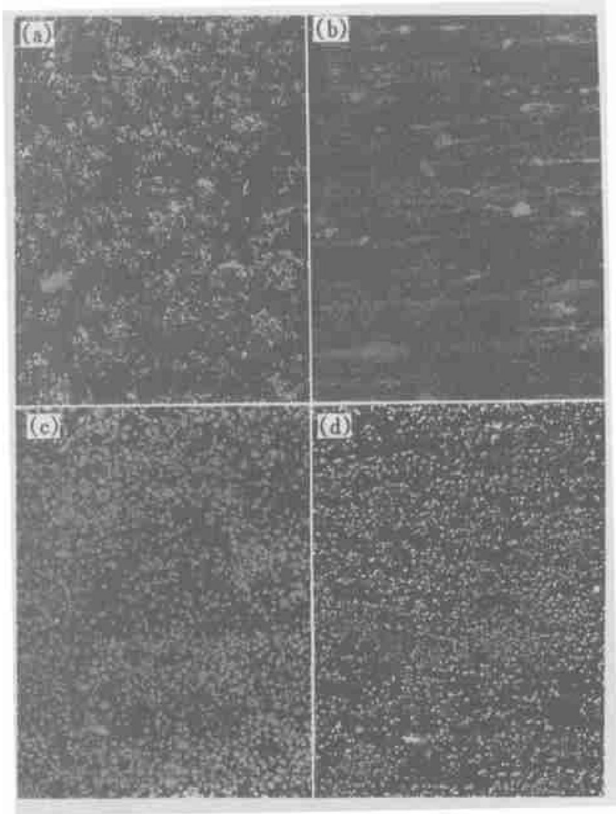

Fig.5 Microstructures of semi-solid extruded composites after T6 treatment
(a) —Perpendicular to the extrusion direction(φ_f = 0.05);
(b) —Parallel to the extrusion direction(φ_f = 0.05)
(c) —Perpendicular to the extrusion direction(φ_f = 0.10);
(d) —Parallel to the extrusion (φ_f = 0.10)

deformation. However, with the increase in TiC particle volume fraction the elongation of composite rods obviously decreases, but still being enough for practical applications.

4 CONCLUSIONS

1) Sound composite rods were successfully fabricated under suitable semi-solid extrusion process parameters.

2) A proper punch velocity well matching the solidification speed of composite slurry is necessary to fabricate composite rods, which can ensure that the composites in the deformation zone are constantly partially solidified.

3) The uniform distribution and no fracture of TiC particles in the matrix were observed due to the advantages of CRM and semi-solid extrusion process.

4) The strength of TiC_p/2024Al composite is much higher than that of the unreinforced 2024 aluminum alloy and increases with the enhancement of the amount of TiC particles. The elongation of TiC_p/2024Al composite is much lower than that of the unreinforced alloy, but still being enough for practical applications.

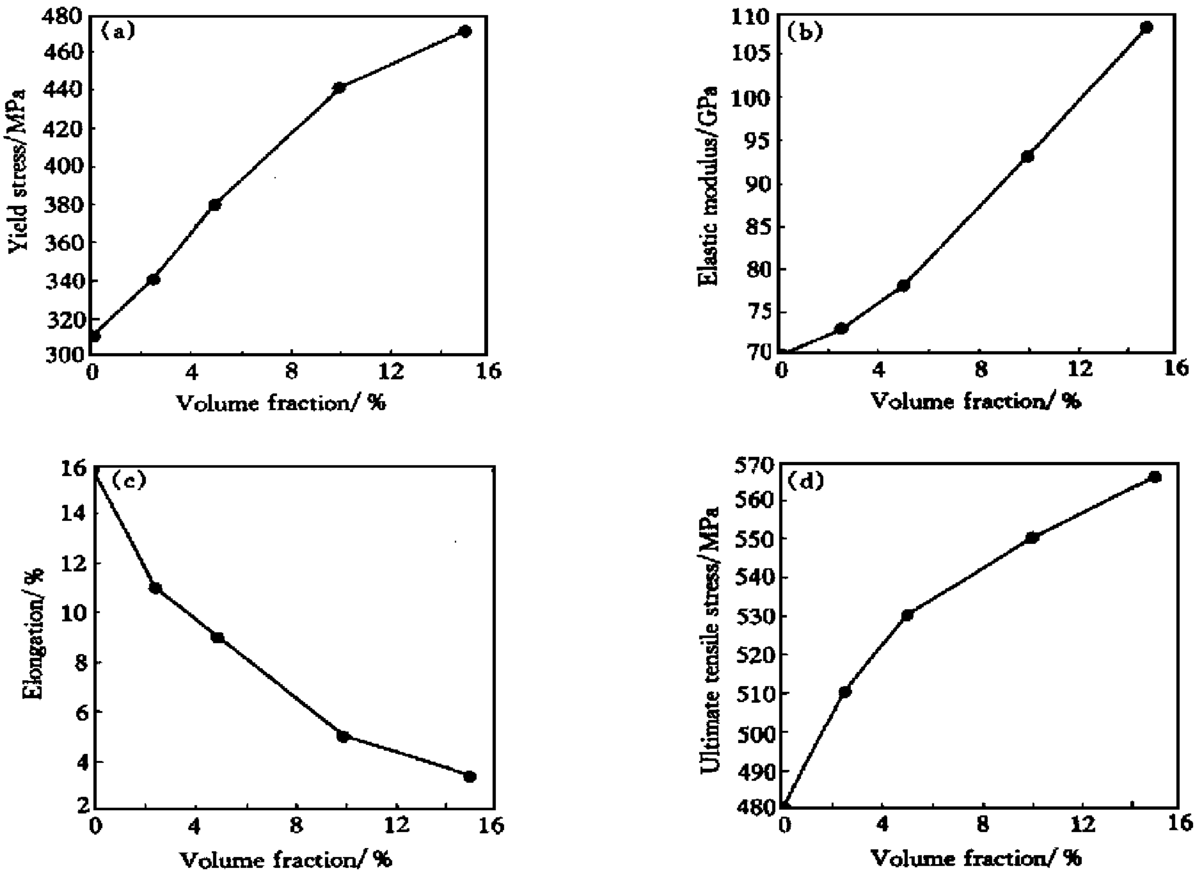

Fig.6 Effects of volume fraction on mechanical properties of metal matrix composite rods

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