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Forming of tubes and bars of alumina/LY12 composites by liquid extrusion process①

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Abstract: Tube and bar products of aluminum alloy composites reinforced by alumina short-fiber were formed in a single process with liquid extrusion technology. The microstructure verifies that the reinforcing effect is obvious in the deformation direction since fibers are distributed along this direction, which is resulted from the flow and crystallization under pressure of liquid metal and large plastic deformation of solidified metal in the process. The interface between fiber and matrix belongs to mechanical bonding. The fractograph demonstrates ductile mode. Liquid extrusion process opens up a new way for fabricating tube, bar and shaped products.

Key words: liquid metal extrusion; aluminum matrix composite; tube and bar
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1 INTRODUCTION

Due to the increased use of discontinuous reinforcement reinforced metal matrix composites, their fabrication techniques have been subjected to a continuous development during the last few years[1-4]. A variety of methods for producing this kind of composite has been available. Among them, fabrication using powder metallurgy or liquid metal forging method has a potential advantage to achieve first-rank properties[5, 6]. But tube, bar and shaped products can't be formed directly by the two technologies and the second process such as squeezing or rolling or other processes is needed. Since there exists the reinforcing phase, the interface bonding between reinforcing phase and matrix will be influenced by the second heating or solid-state deformation due to the mismatch of their deformation resistance and expansion coefficient, and even the material property will also be affected. How to solve this problem is one of the subjects that have been studiously explored all the time by the composite researchers[7-9]. In this paper, composite tube and bar products of LY12 alloy reinforced by alumina short-fiber are fabricated by liquid metal extrusion process, which was developed on the basis of combination of casting, liquid metal forging and hot extrusion.

2 EXPERIMENTAL

The experiments of forming tube and bar were carried out on 3.15 MN hydraulic pressure with special experimental equipment by choosing alumina short fiber (the composition and properties are listed in Table 1) as reinforcement and LY12 alloy (the composition is listed in Table 2) as matrix. The tensile property of specimens cut from the experimental product was measured. Its micrographs and fractographs were examined by SEM.

2.1 Preparing reinforcing preform

Firstly, the mixture of the silicasol aqueous solution and fiber was poured into the blender and stirred strongly to make them uniform, and then they were poured into the forming die under pressure. Next, residual aqueous solution was removed by putting wet preform into dry box, drying at 150-200 ℃ and sintering at about 700 ℃ to remove organic agglomerant. At last, the fiber preform with certain strength could be obtained after cooling.

2.2 Infiltration process of liquid metal

The forming process of composite tubes and bars by liquid extrusion is as follows: 1) liquid metal is infiltrated into the preform under pressure; 2) liquid metal flows in the preform; 3) liquid

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Table 1 Composition and properties of alumina short fiber

$w(Al_2O_3)$ /%	$w(SiO_2)$ /%	$w(Fe_2O_3)$ /%	$w(K_2O+Na_2O)$ /%	Crystallography	φ(Spherical fiber slag) /%	Fiber size/μm	Fiber length/mm	Density/ $(kg\cdot m^{-3})$	Tensile strength/ MPa
80	< 20	< 0.006	< 0.007	α-Al_2O_3, $3Al_2O_3$, $2SiO_2$	< 5	3 − 10	> 50	30 − 50	1 130

Table 2 Chemical composition of LY12 alloy

$w(Cu)$/%	$w(Mg)$/%	$w(Mn)$/%	$w(Zn)$/%	$w(Al)$/%
3.8 − 4.9	1.2 − 1.8	0.3 − 0.9	0.3	Bal.

metal is filled into the tiny holes of the preform further under high pressure; 4) liquid metal is solidified under pressure and combines with the reinforcing material during deformation; and 5) the tube and bar products are formed. Valid control of infiltration process is the key of this forming technology in the whole process.

The infiltration of liquid metal into the fiber preform is a fairly complex physical process in which the distribution state of reinforcing fiber is variable. The defects such as the pores in composites because of incomplete infiltration may be led, and then the structure and property of products can be influenced. In fact, the infiltration of liquid metal into the fiber preform is held back by diversified resistances, for instance, capillary action, viscous resistance, solidification resistance, air back pressure, frictional resistance, and so on. The infiltration process cannot be finished until these resistances are overcome by infiltration pressure.

The infiltration process of liquid metal is not only determined by infiltration pressure, but also related to the distribution state and interface wettability of the fiber[10]. If the fiber is distributed uniformly, fiber gap can be filled uniformly by liquid metal whether it is wet or not between liquid metal and fiber in respect that the infiltration motivity or resistance formed by the capillary action is same everywhere, and so do other kinds of resistances. Otherwise, liquid metal will flow into interspaces with large radius and then penetrate along the transverse direction to fill in the interspaces inside the fiber bundles.

According to the Kelvin equation:

$$\Delta p_{\sigma} = 2\sigma \sum_{i} \frac{1}{r_i} \qquad (1)$$

where Δp_{σ} is the total differential pressure of surface resulted from the curvature radius r_i of liquid surface, σ is the liquid surface energy.

On the other hand, when liquid metal and fiber are non-wetting, capillary action becomes infiltration resistance. If the interspaces among the bundles are bigger, namely, the curvature radius is bigger, the capillary resistance will be smaller. Otherwise, the bigger infiltration resistance will result from the small hole inside the fiber bundles, which will increase the infiltration velocity difference between inside and outside of the bundles. The more the non-uniform fiber distribution is, the more the non-uniform infiltration degree is.

When liquid metal and fiber are wetting, capillary action becomes infiltration motivity. The capillary motivity in big interspaces among the bundles is smaller than that in small interspaces inside the bundles. But the difference will reduce the infiltration velocity discrepancy, resulting in the improvement of the infiltration non-uniformity. So, the fiber should be distributed as uniformly as possible when manufacturing fiber preform[11].

2.3 Technological parameters

Many difficulties in technique need to be broken through when the liquid extrusion process is used for forming composite tubes and bars. Except for the above points, how to combine the liquid infiltration and extrusion into one working procedure to get high-performance tubes and bars from liquid is also very crucial. Study has shown that the followings should be arrived: 1) complete infiltration of liquid metal into the fiber preform must be made before extrusion; 2) the interior liquid-state or semi-solid state metal should maintain isostatic pressure state after applying pressure; 3) the deformation region is in quasi-solid state and no liquid metal is extruded out near the entrance of the forming die; 4) the microporosities of matrix metal are further removed and non-wetting phenomenon between fiber and matrix material is improved by the large deformation in the extrusion process; 5) suitable processing parameters need to be decided to ensure that the forming process will go on successfully and sound composite product will be extruded out.

According to the technology peculiarity of forming composite by liquid extrusion, the forming dies for tubes and bars were designed respectively. Both of them relied on the same principle (as shown in Fig. 1). The liquid infiltration and extrusion processing parameters include preheat temperature of the fiber preform, preheat temperature of die, pouring temperature of the metal, infiltration pressure, infiltration time, extrusion velocity and extrusion pressure, and so on. Waste product will come into being if any parameter is not controlled properly[12].

Tubes and bars of aluminum matrix composites (as shown in Fig. 2) were formed respectively after iterative extrusion experiments, and then this technology was established (as listed in Table 3).

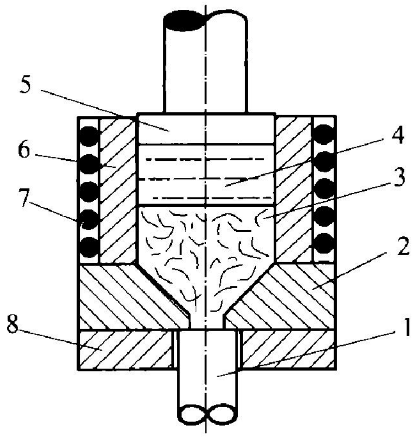

Fig. 1 Schematic of experimental facility for liquid extrusion of composite bars
1—Ejector rod; 2—Forming die; 3—Fiber preform; 4—Liquid metal; 5—Punch; 6—Extrusion cylinder; 7—Heating installation; 8—Underlaying board

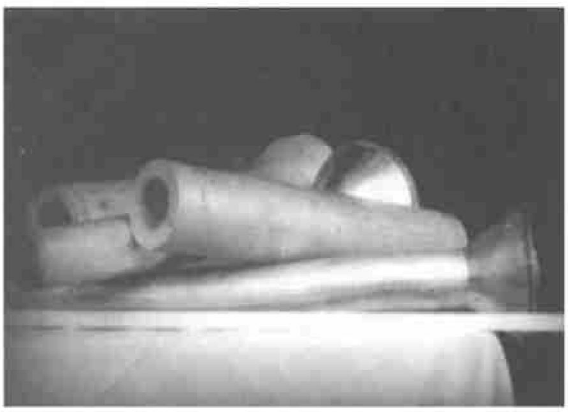

Fig. 2 Photo of composite tubes and bars formed by liquid extrusion

Table 3 Technological parameters for liquid extrusion of composite tube and bar

Product type	Volume fraction of fibers/%	Preheat temperature of fiber/℃	Preheat temperature of forming die/℃
Tube	10-15	600-680	250-300
Bar	10-15	550-650	250-300

Product type	Preheat temperature of extrusion cylinder/℃	Pouring temperature/℃
Tube	300-350	800
Bar	300-350	780

Product type	Infiltration pressure/MPa	Infiltration time/min	Extruding velocity/($mm \cdot s^{-1}$)
Tube	1-3	3	3-5
Bar	1-2	3	3-5

3 RESULTS AND DISCUSSION

3.1 Mechanical properties

Properties of alumina/LY12 composites that were fabricated by liquid extrusion are listed in Table 4. It can be seen that the material properties are improved in some degree. The tensile strength is increased by 15% at most, elongation is substantially improved at the same time and the high-temperature property and friction-resistant property will be also improved according to the characteristics of metal matrix composites, so this technology for producing tube and bar composites is proved to be feasible.

Table 4 Properties of alumina/LY12 composites fabricated by liquid extrusion process

Material	Tensile strength/MPa	Elastic modulus/GPa	Elongation/%
LY12 (Quench-aging)	430	50.2-53.8	7.0
Alumina/LY12 (as extruded)	305-329	71.3-75.5	9.5-12.7
Alumina/LY12 (Quench-aging)	416-495	66.2-75.2	9.9-16.6

3.2 Microstructure

From the metallograph of alumina/LY12 composite by liquid extrusion as shown in Fig. 3, it can be seen that matrix microstructure is fine, and fiber distribution is uniform and ordinate in some degree. The fibers along axial (extrusion deformation) direction are quasi-unidimensional, which indicates that fibers and liquid metal undertake three direction pressure during the extrusion process and the fibers move and turn the direction with the flow of liquid metal before solidification. This distribution status is helpful for improving the material strength along the deformed direction. Simultaneously, the rupture and deformation of fibers can be observed obviously in Fig. 3, which is probably the result of large deformation of quasi-solid state and solidified metal. Certain relative movement between the metal and the reinforcing fiber occurs because of their different deformation capabilities, that is to say, metal is prone to undergo plastic deformation and to flow, but fiber is difficult to deform, so they can't be concerned in the deformation process. Fibers will be ruptured and broken when the applied frictional stress or shear stress exceeds its strength limitation, which are resulted from the lower flow velocity of the fibers than that of the metal. The necking deformation of partial fiber can also be observed from this figure. There are two possibilities. One is that this necking-down is formed in fiber fabrication processing, but it is not discovered from the metallograph of alumina/LY12 composites prepared by liquid forging. The other is that the fibers are applied just spherical static pressure and surface friction, but not shear stress because the direction adjustment of fiber during the movement and direction turning before solidification is in consist with the deformation flow direction of solidified metal. This stress state motivates the fibers to produce simple extending deformation. Therefore, suitable stress state leads the fibers, which have little plasticity in general condition, to undergo obvious plastic deformation.

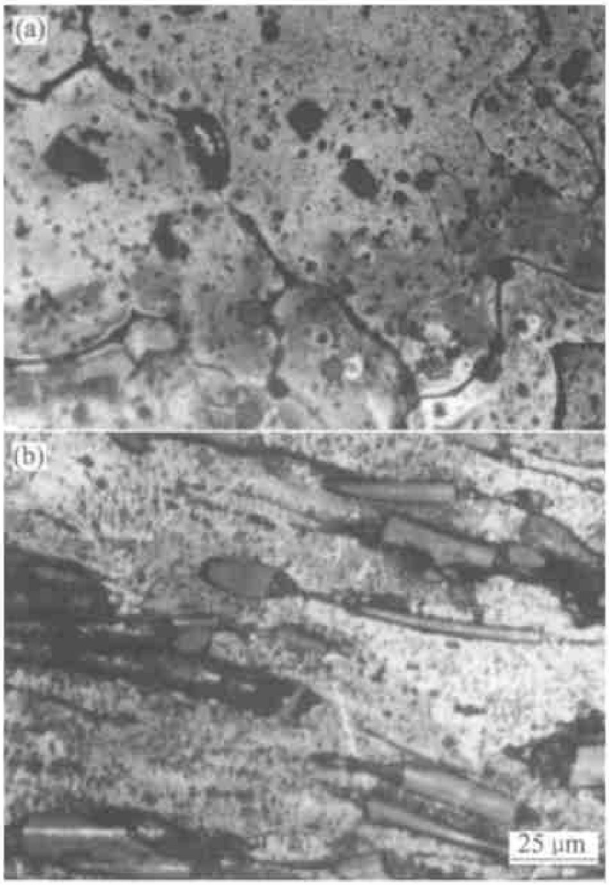

Fig. 3 Microstructures of alumina/LY12 composite prepared by liquid extrusion
(a) —Rupture of fibers; (b) —Deformation of fibers

It should be said that the breakage of the fiber caused by the relative movement of fiber and metal goes against the property improvement of the composite, but the movement and direction turning of fiber in the flow of liquid metal and plastic deformation of solidified metal are beneficial to improve the strength of composite along this direction, especially the existence of fibers which undergo necking-down deformation has significant impact on the improvement of property in that direction. Consequently, the comprehensive function can result in higher properties of composite.

3.3 Bonding of fiber and matrix

According to the above analysis, there exists the relative movement between fiber and matrix metal. It can be seen that the bonding model between them belongs to mechanical combination, which is verified by Fig. 4. The bonding interface is closer (as shown in Fig. 4(a)) under higher spherical static pressure, which plays a reinforcing role in making the composite property be improved in some degree. It can be seen from Fig. 4 that there seems no reaction or no severe reaction at the interface between fiber and metal. Since the fiber must be preheated for the infiltration of liquid metal and it must contact with liquid metal directly under high pressure, it should be easier to produce interface reaction, which would result in the emergence of brittle phase and the weakening of fiber reinforcing effect. No severe interface reaction is expected when composite products with high-performance are fabricated.

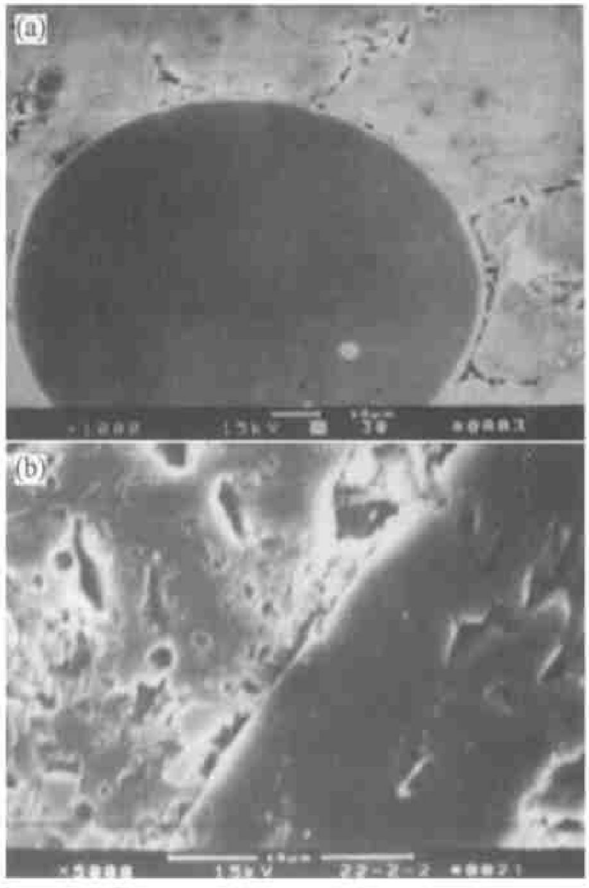

Fig. 4 Interfacial statuses between fiber and matrix metal
(a) —Low magnification; (b) —High magnification

3.4 Fractographs

The SEM observation shows that the tensile fracture samples with higher performance take on obvious cup-shaped, which belongs to ductile fracture (as shown in Fig. 5). The metal around the fiber shows lacerated shape, but the fiber rupture is brittle and is slightly pulled out partially. It proves that the combination of the interface is better, which makes the fabricated composite have both certain composite effect and plastic deformation capability, and fit for engineering application.

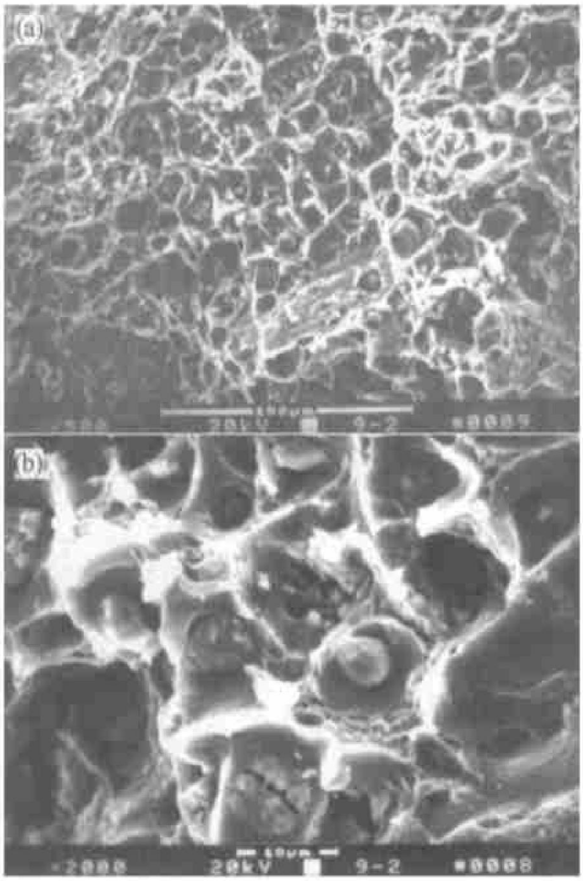

Fig. 5 SEM fractograph of normal extension
(a) —Low magnification; (b) —High magnification

Many kinds of defects were found in the lower performance samples. Firstly, the material property is influenced greatly by the existence of spherical fiber slags and big diameter fibers (> 10 μm, as shown in Fig. 6). Spherical fiber slags in the composites not only doesn't have reinforcing effect, but also will become obvious crack source because of its low property and big brittleness. From Fig. 6, it can be seen that the breakup of spherical fiber slag is caused in plastic deformation process, though bigger spherical static pressure is exerted on. So serious stress concentration is caused in the tensile process and then the weakening of material. In addition, reinforcing effect will also be affected by the uneven diameter and mutual conglutination of fiber observed in the fracture (as shown in Fig. 6(c)). So the quality of fiber is the main factor that influences reinforcing effect. Reinforcing effect will be improved in a large scale and composite product with steady property will be obtained if the above problems are settled.

Reinforcing effect will also be influenced by unsuitable technology. Fig. 6(c) shows that local conglomeration of fibers comes into being since fiber decentralization is inadequate in the preform forming process. Material property is decreased greatly because there is no metal inside the conglomeration fibers, and then fiber not only can't have reinforcing effect, but also become defect region. So adequate dispersion of fiber in preform fabrication is terribly crucial.

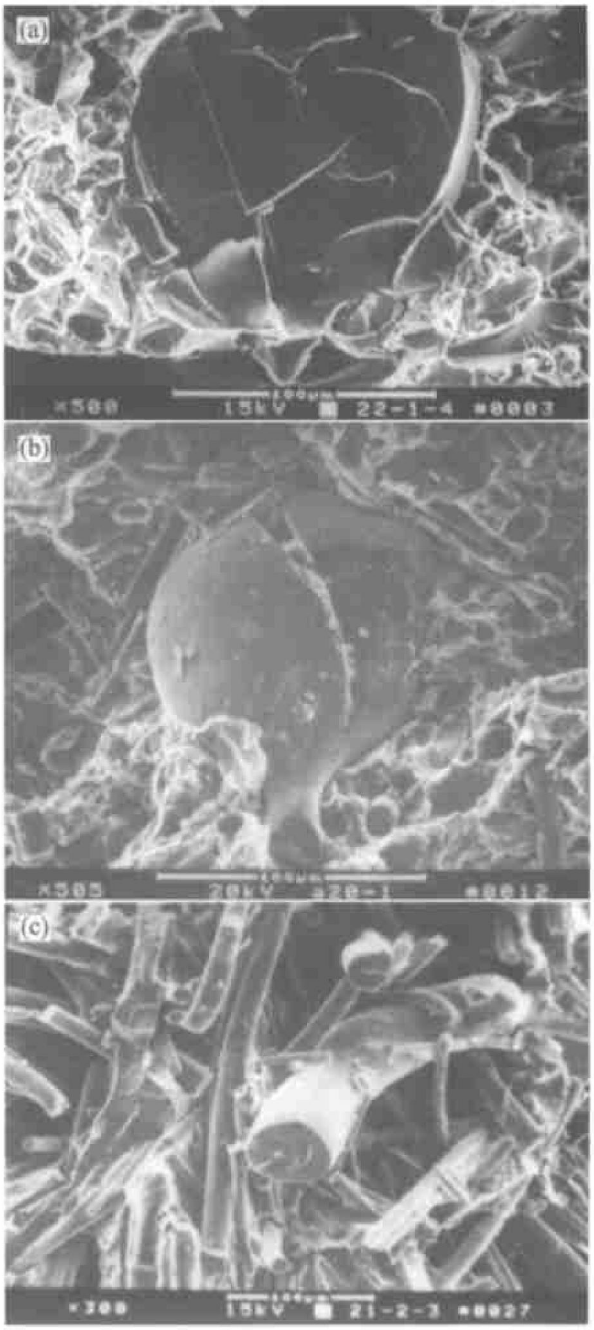

Fig. 6 SEM fractograph of some defects inside material
(a) —Breakup of spherical fiber slag;
(b) —Spherical fiber slag existed;
(c) —Fiber diameter being uneven and decentralization being insufficient

4 CONCLUSIONS

1) Short fiber reinforced composite bars can be formed directly with liquid extrusion process, which offers a feasible method for the fabrication of this kind of products. The most important of all, working procedure can be reduced, and energy and cost can be saved by this technology.

2) Fibers in the products are distributed along

the deformed direction because of the movement caused by liquid metal flow and the direction turning by the deformation process of solidified metal. Furthermore, fiber is deformed and even ruptured because of the compress stress and friction of matrix metal, but the reinforcing effect is not affected obviously.

3) Interfacial bonding between fiber and matrix is mechanical. There is no severe interface reaction.

4) The existence of spherical fiber slags and big diameter fibers is very harmful. The breakup of spherical fiber slags and local stress concentration will be caused by large plastic deformation, resulting in the decrease of material property.

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