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Preparation of heat-resistant aluminum alloy pipe blanks by multi-layer spray deposition①

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[Abstract] A heat-resistant aluminum alloy pipe blank with dimensions of d700/300 mm × 1 200 mm was prepared by the multi-layer spray deposition technology. Optical microscopy, X-ray diffractometry and transmission electron microscopy were used to analyze its morphologies and microstructures. The results show that the microstructures of the pipe blank are homogeneous and the precipitates are uniformly-distributed d25 ~ 70 nm spherical or sphere-like $Al_{12}(Fe,V)_3Si$ particles, its mechanical properties at room temperature and 350 ℃ after densification by extrusion are $\sigma_b = 412$ MPa, $\delta = 7.6\%$ and $\sigma_b = 187$ MPa, $\delta = 7.6\%$, respectively. The analyses indicate that the proper match of the motion rates of atomizer and substrate can produce deposited blanks with uniform thickness and relatively high cooling rate.

[Key words] heat-resistant aluminum alloy; pipe blanks; spray deposition; rapid solidification
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1 INTRODUCTION

The FVS series of heat-resistant aluminum alloys were developed using the planar flow casting by American Allied Signals Company in 1986[1]. Because of their excellent strengths at room temperature and high temperatures, high elastic moduli and good corrosion resistance, they have found wide applications in aerospace, aviation and automobile industries. Their excellent properties mainly stem from the dispersion strengthening of dispersively distributed, thermally stable and fine $Al_{12}(Fe,V)_3Si$ silicide particles produced by rapid solidification. However, because of the limitations of forming conditions, the planar flow casting can only be used to produce some small parts and components. Furthermore, the procedures are complex and the production period is long, therefore its development and applications are limited.

The spray deposition technology was first proposed in 1968 and reported in 1970 by Prof. A. Singer of Swansea University. It is a direct preparation method of near-net shape blanks that lies between ingot metallurgy and powder metallurgy; it combines some advantages and overcomes some shortcomings of both. The characteristics of this technology include high cooling rate(10^3 K/s), slight segregation, fine microstructure and low degree of oxidation[2,3]. But because the dimensions of deposited blanks are limited by forming principle and apparatus, it is difficult to produce large thick-walled pipes, especially heat-resistant aluminum alloy pipes with high demand for cooling rate.

The multi-layer spray deposition technology was proposed and developed by Prof. CHEN et al in the early 1990s[4,5]. The schematic diagram of the multi-layer spray deposition technology for manufacturing large-scale pipe blanks is shown in Fig.1. The largest difference between the multi-layer spray deposition technology and the conventional spray deposition technologies lies in the motion modes of the atomizer and the substrate. In the conventional spray deposition processes, the atomizer keeps motionless and only the substrate moves (When vibrating nozzle is used, the atomizer keeps motionless, and the nozzle vibrates fast.), therefore the scanning range of the atomized spraying flow is restricted. While in the multi-layer spray deposition process, the atomizer makes reciprocal rectilinear motion along the substrate

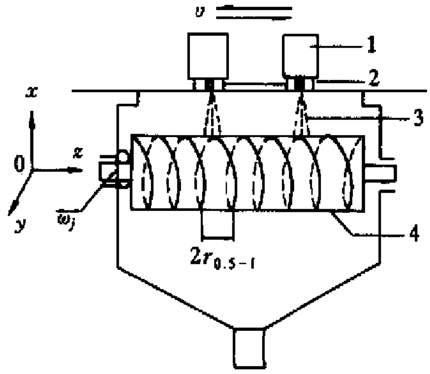

Fig.1 Schematic diagram of multi-layer spray deposition technology for preparing pipe blanks
1 —Clay-graphite crucible; 2 —Atomizer;
3 —Spraying flow; 4 —Deposition pipe blank

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surface, thus the scanning range of the spraying flow is large, consequently the dimensions of the blanks are also large. So far, a large-scale heat-resistant aluminum alloy blank with dimensions of d700/300 mm × 1 200 mm (external diameter/internal diameter × length) has been successfully manufactured[6]. The aim of this work is to analyze the principle of the multi-layer spray deposition technology and study the properties of the pipe blank prepared by this technology.

2 EXPERIMENTAL

The rotating axis of the pipe preparation apparatus was covered with 1 200 mm long pretreated aluminum alloy substrate pipe, then preheated to 400 ~ 500 ℃. Appropriate motion paths of deposition were obtained by adjusting the turning rate of the substrate ($\omega_j = 20 \sim 100$ r/min) and the motion rate of the atomizer ($v = 0.06 \sim 0.12$ m/s). After heated to 1 000 ℃, the molten FVS alloy was poured into a clay crucible, then sprayed at a flow rate of 0.06 ~ 0.1 kg/s from a deposition height of 120 ~ 300 mm in a nitrogen atmosphere of 0.8 ~ 1.0 MPa. The spraying was stopped when the expected dimension of the pipe blank was reached.

Cross-sectional microstructure of the deposited pipe blank was observed or analyzed by optical microscopy, X-ray diffractometry and transmission electron microscopy. After the pipe blank was densified by extrusion, tensile specimens were prepared according to GB/T4338-1995 and the tensile tests were performed at room temperature and 350 ℃.

3 RESULTS

A material object photograph of the pipe blank is shown in Fig.2. The surface is smooth, and the diameter is uniform except at the ends. The cross-sectional microstructures are shown in Fig.3. It can be seen that there exist obvious pores at the deposition interfaces in the first deposited 1 ~ 3 layers (about 0.5 mm thick, Fig.3(a)), then the interfaces disappear and the small pores are distributed uniformly (Fig.3(b)). The relative density of the pipe blank is 87 % ~ 90 %. The microstructure of the pipe blank is homogeneous, there are not coarse precipitates but pre-solidified powders with sizes of 3 ~ 20 μm (Fig.3(c)). XRD analysis and TEM observation (Fig.4) indicates that, in the pipe blank there are only the matrix phase α(Al) and a silicide α-$Al_{12}(Fe,V)_3Si$, and the spherical or sphere-like precipitates with sizes of 25 ~ 70 nm are uniformly distributed in the matrix phase. The microstructures of the pipe blank after extrusion are presented in Fig.5. It can be seen that, on the transverse section the precipitates are fine and uniformly distributed, while on the longitudinal section there are distributed fine banded microstructures.

Chemical analysis shows that the main composition of the pipe blank is Al-8.3Fe-1.3V-1.7Si. Its oxygen and nitrogen contents are 0.04 % and 0.002 %, respectively. This oxygen content is largely below that of powders prepared by powder metallurgy (about 0.15 % ~ 0.2 %) and slightly above that of the deposits prepared by the conventional spray deposition technologies (about 0.01 % ~ 0.02 %)[7].

The mechanical properties of the large-scale pipe blank after extrusion are listed in Table 1. These values are equal to those of small pipe blank (d300/130 mm × 400 mm) prepared by the same technology, but are obviously better than those of the same alloy pre-

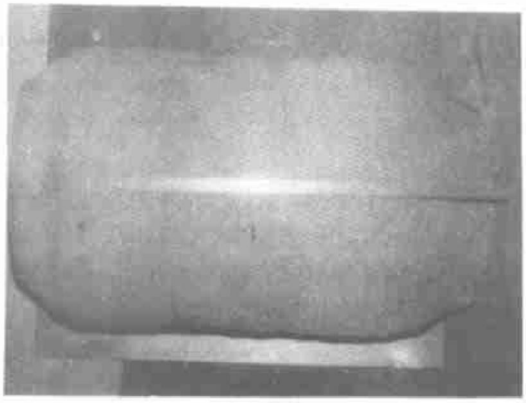

Fig.2 Material object photograph of d700/300 mm × 1 200 mm pipe blank prepared by multi-layer spray deposition technology

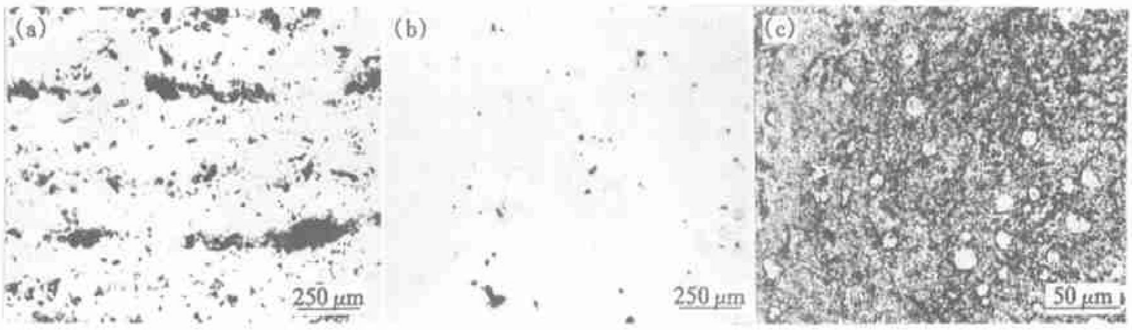

Fig.3 Morphologies of pipe blank

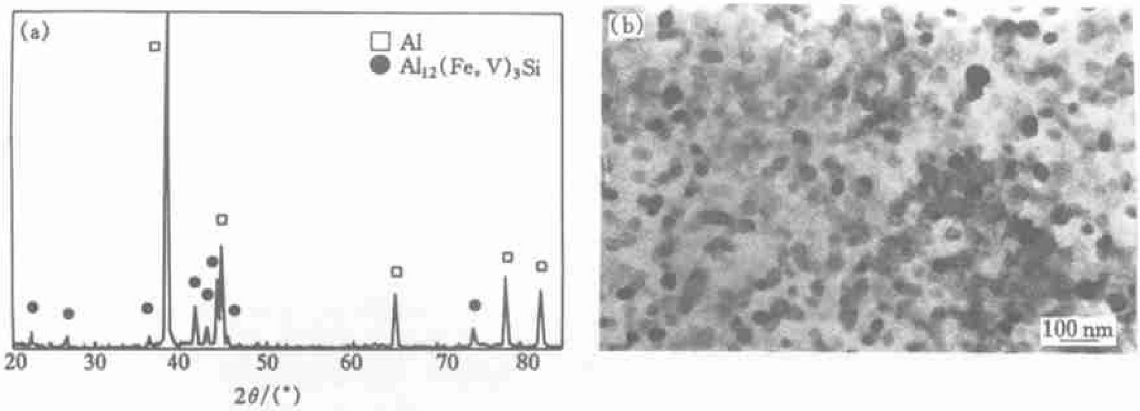

Fig.4 XRD pattern (a) and TEM morphology (b) of pipe blank

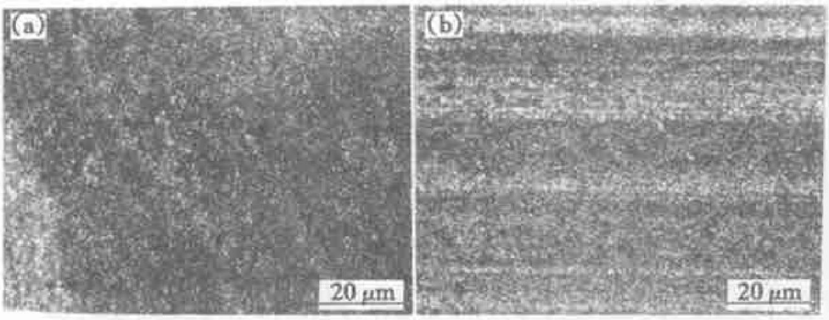

Fig.5 Microstructures of pipe blank after extrusion
(a) —Transverse section; (b) —Longitudinal section

Table 1 Mechanical properties of heat-resistant aluminum alloy pipe blanks

Preparation method	Room temperature mechanical properties			High temperature mechanical properties			
	$\sigma_{0.2}$/ MPa	σ_b/ MPa	δ/ %	$\sigma_{0.2}$/ MPa	σ_b/ MPa	δ/ %	Notes
Planar flow casting	407	448	17.0	165	186	19.0	371 ℃
Conventional P/ M	353	398	7.2	213	222	6.8	420 ℃
MLSD small pipe	330	414	5.7	166	188	7.2	350 ℃
MLSD large pipe	319	412	7.6	156	187	7.6	350 ℃
Conventional spray deposition	271	313	18.0	149	161	22.0	260 ℃

pared by the conventional spray deposition technologies, some indexes even approach or exceed the corresponding values by powder metallurgy.

4 DISCUSSION

4.1 Motion paths of spray deposited liquid droplets

In the multi-layer spray deposition process for preparing pipe blanks, the atomizer and the substrate move simultaneously. The spraying flows scan the deposition surface several to several dozens of times, and the deposited blanks are formed layer by layer. While in the conventional spray deposition processes for preparing pipe blanks, the deposited blanks are formed by single deposition part by part[9]. Different matches of the motion rate of atomizer and the turning rate of the substrate can produce different motion paths of spray deposited liquid droplets, e.g. sinusoid and helix. In order to obtain blanks with uniform diameters and excellent qualities, every deposition on the whole deposition surface must be uniform. In preparing large pipe blanks, the motion distance of the atomizer is relatively long, the situation of the deposition is easy to control by adopting the helical deposition path. The deposited blank is formed by the superposition of multi-layer deposition, and Eq.(1) describes the motion paths of the spray deposited liquid droplets, where v is the transitional velocity of the atomizer, t is the scanning time and r is the radius of the deposition surface. The scanning curve is shown in Fig.1.

$$\left.\begin{aligned} z &= vt \\ x^2 + y^2 &= r^2 \end{aligned}\right\} \tag{1}$$

The spacing of the motion paths is an important controlling factor to ensure the uniformity of each deposition layer. Considering that the matter flow density of the atomization cone presents a Gauss distribution in space (Fig.6)[10,11], it is clear that, with increasing spraying height, the mass flux at the spraying center decreases, while the half-width ($r_{0.5\text{-f}}$) of the mass flux profile, which is defined as the radius where the mass flux is 50 % of that on the axis, increases. If the pitch of the motion path of the spraying flow equals 2 $r_{0.5\text{-f}}$, then the scanning of the spray flow can be approximately considered a uniform helical motion with a diameter of 2 $r_{0.5\text{-f}}$ and a density which equals the axial density of the atomization cone. After one deposition, the deposition surface is smooth and the deposition interface between two consecutive depositions can be eliminated fairly well. To realize this motion, the motion rate of the atomizer (v) and the turning rate of the substrate (ω_j) must satisfy the following expression:

$$v \cdot 2\pi/\omega_j = 2r_{0.5\text{-f}} \tag{2}$$

or

$$v = \omega_j r_{0.5\text{-f}}/\pi \tag{3}$$

If $v > \omega_j r_{0.5\text{-f}}/\pi$, part of the deposition surface will have no deposit after one cycle of deposition, while if $v < \omega_j r_{0.5\text{-f}}/\pi$, then part of the scanning region of the atomization cone will overlap. Although uniform deposition layers can be formed on the deposition surface, the cooling rate of the deposited blank is affected. If $v = \omega_j r_{0.5\text{-f}}/\pi$, then after one cycle of deposition, two uniform layers with opposite directions are deposited. The thickness of one cycle, X, can be expressed by

$$X = (m_L/\rho_m A_s)\,T \tag{4}$$

where m_L is the flow rate of liquid droplets, ρ_m the metal density, A_s the area of deposition surface, and T the deposition period. By adjusting the motion rate of the atomizer and the turning rate of the substrate and controlling the scanning rate of the spray flow, the deposition thickness and the situation of the deposition surface can be adjusted.

In preparing long pipe blanks, if single atomizer is used, the scanning distance will be too long and the deposition efficiency will be too low. In order to raise the deposition efficiency, double atomizers can be used to spray at the same time. It can be deduced from the scanning path of single atomizer that, if the distance between two atomizers is even folds of $r_{0.5\text{-f}}$ and equals half of the whole scanning distance, the central joining part of the motion paths of both atomizers will be smooth. Otherwise it will be concave or convex. At both ends of the pipe blank, there appears reduction of diameter. It can be known from the deposition paths of spray flow that, the multi-layer spray deposition technology is suitable for preparing short pipe blanks with large diameters and thick walls, while the conventional spray deposition technologies are suitable for preparing long pipe blanks with small diameters and thin walls.

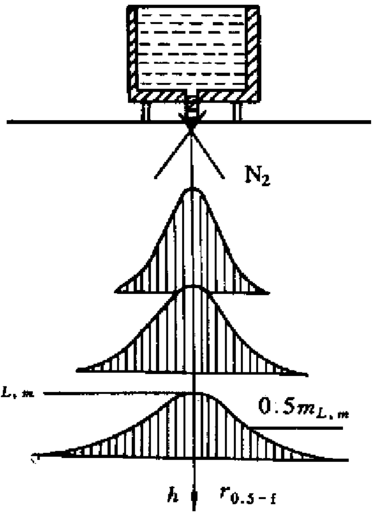

Fig.6 Spatial distribution of mass flux density of atomization cone

4.2 Structure analyses

In the deposition process of pipe blanks, because the interval between two adjacent depositions is relatively long, the previously deposited layer has solidified when the atomized droplets collide with the deposition surface and spread on it, thus the atomized droplets can adhere well to the blank and realize effective bonding. At the same time, the pores at the interface can be filled. In the firstly deposited layers, because the temperature of the deposition substrate is low, the solidification time of the atomized droplets is short; they solidify before filling in the pores, thus it is difficult to eliminate the interface layer. As the deposition process goes on, the temperature of the deposition surface of the pipe blank rises, the solidification rates of the atomized droplets decrease, the liquid can merge well with the deposition surface, thus the layer interface is not obvious. High temperature of the deposition substrate is beneficial to reducing the thickness of the transient zone and improving the homogeneity of the pipe blank. At the same time, high temperature of the substrate helps to improve the wettability between the atomized droplets and the substrate, bring down the thermal stress between the deposited layer and the substrate, and mitigate the peeling off of the deposited layer[12]. The experiments prove that, only when the temperature of the Al-2Si alloy substrate is higher than 723 K, can the Al-Fe-V-Si alloy adhere well to the substrate and the transient layer will be thin.

4.3 Analyses of precipitates and mechanical properties

In the preparation process of pipe blanks by the conventional spray deposition technologies, the atomizer moves slowly unidirectionally, the deposition surface is small, the heat dissipation rate of the deposited blank is slow, and there is a thin layer of liquid on the deposition surface, therefore the solidification rate of the liquid is small, generally 1 ~ 10 ℃/s[13]. Consequently, the precipitates in the blank is coarse, even there may appear coarse spinel phase $Al_{13}Fe_4$. While in the multi-layer spray deposition technology, the deposition area is large, the thickness of each deposition is very thin, the heat is dissipated fully by conduction of the substrate and convection of the deposition surface, thus the solidification rates of the liquid droplets are relatively high. Consequently, the $Al_{12}(Fe, V)_3Si$ precipitates are small and no $Al_{13}Fe_4$ phase appears. In a word, in the preparation process of FVS series of heat-resistant aluminum alloys which are sensitive to the cooling rate, although the multi-layer deposited blanks have relatively low densities, they still can obtain good mechanical properties after densified by the following techniques such as extrusion.

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