

Microstructure evolution and solidification behaviors of A2017 alloy during cooling/stirring and rolling process

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Abstract: A novel semisolid rheo-rolling process of A2017 alloy was achieved by combining the shape rolling mill with the vibrating sloping plate device. The microstructure evolution and solidification behaviors during the process were investigated. The high cooling rate caused by the sloping plate and stirring action caused by the vibration and metal flow lead to a high nucleation rate as well as two primary grain growth patterns, direct globular growth as well as dendrite growth and subsequent breakage, which causes the formation of fine spherical or rosette primary grains. During the rolling process, the grains of the strip were elongated. The primary grain size of A2017 alloy strip increases with the increment of casting temperature. When the casting temperature was between 650 °C and 660 °C, A2017 alloy strip with good quality was produced by the proposed process. The microstructures of the strip are mainly composed of spherical or rosette grains.

Key words: A2017 alloy; semisolid; sloping plate; rolling; microstructure; microstructure evolution; solidification

1 Introduction

Rheo-rolling process is developed based on the rolling and semisolid forming processes. Therefore, it has some advantages. Firstly, because the temperature of semisolid alloy is much lower than that of liquid alloy, the solidification time of semisolid alloy is shorter than that of liquid alloy, and the rolling speed can be improved over roll casting greatly. Secondly, because round solid grains take part in deformation process during rheo-rolling process, the mechanical properties of the product prepared by rheo-rolling process are much higher than those by roll casting process [1–3]. However, how to prepare good quality semisolid slurry with low cost and high efficiency becomes an important subject for developing rheo-rolling process. Therefore, many slurry preparation processes have been developed, such as mechanical stirring [4], magneto hydro dynamic stirring [5], melt conditioner direct chill casting [6,7]. As one of slurry preparation processes, sloping plate process has obvious advantages of high efficiency and low cost. During this process, the alloy melt is cast onto a sloping plate, and under the actions of the cooling and melt flow,

the semisolid alloy can be prepared [8]. HAGA [9] has installed a sloping plate device onto a roll casting mill to develop the semisolid rolling process. KAPRANOS et al [10] improved this technique. However, the problems of slurry adhesion on the plate surface and the liquid segregation commonly occurring in the semisolid rolling should be resolved.

The sloping plate process and roll casting process were developed based on the previous studies. New types of vibrating sloping plate and shape rolling mill were adopted, and a novel rheo-rolling process was developed. This process has two main advantages: 1) The semisolid alloy needs short solidification time, so the process is expected to be developed as a high-speed semisolid roll-casting technique; 2) The microstructure and the mechanical properties of the product are better than those produced by conventional roll casting. The microstructure formation mechanism and the effects of technical parameters on microstructure of the A2017 alloy strip were investigated.

2 Experimental

The experimental equipment is the self-designed

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device of semisolid rheo-rolling. The nominal diameter of the rolls is 400 mm, and the rolling speed is 22 m/min. The cross section sizes of the strip are 4 mm×160 mm. The melt was poured onto the surface of the vibrating sloping plate. The semisolid slurry consisting of fine non-dendrites and remnant liquids can be obtained due to the high cooling rate caused by the sloping plate as well as stirring action caused by the vibration and metal flow. The semisolid slurry flowed directly into the roll gap between the convex and the concave rolls, as shown in Fig. 1. The chemical compositions of A2017 alloy are Cu 4, Mn 0.6, Mg 0.6, and Al balanced. The liquids and solidus temperatures of the alloy are 641 °C and 513 °C, respectively. In order to study the microstructure formation mechanism of A2017 alloy on the sloping plate surface, the alloy slurries at different positions on the sloping plate were taken and quenched, and the inner microstructures of the products produced under different process parameters were also observed. The specimens were polished and etched by a solution of 2 mL HF + 3 mL HCl + 5 mL HNO₃ + 190 mL H₂O. The microstructure observation was performed under an OLYMPUS PMG51 metallographic microscope.

3 Results and discussion

3.1 Microstructure evolution during process

When the casting temperature was 650 °C, the

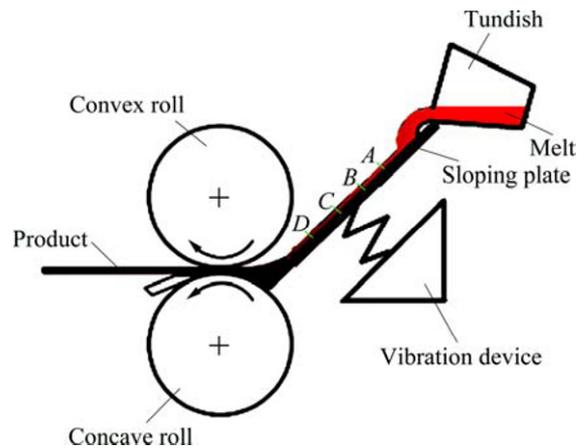


Fig. 1 Schematic diagram of semisolid rheo-rolling

microstructures of the quenched melt at different positions on the sloping plate surface are shown in Fig. 2. The primary grains on the sloping plate transformed from dendrites to fine spherical or rosette grains gradually, and the grains size also decreased with the alloy flow from upper position *A* to the bottom position *D* shown in Fig. 1.

It was believed that the formation of fine and spherical microstructure was favoured by a large number of heterogeneous nucleation sites on the cooling sloping plate [11,12]. But there was no clear evidence. Actually,

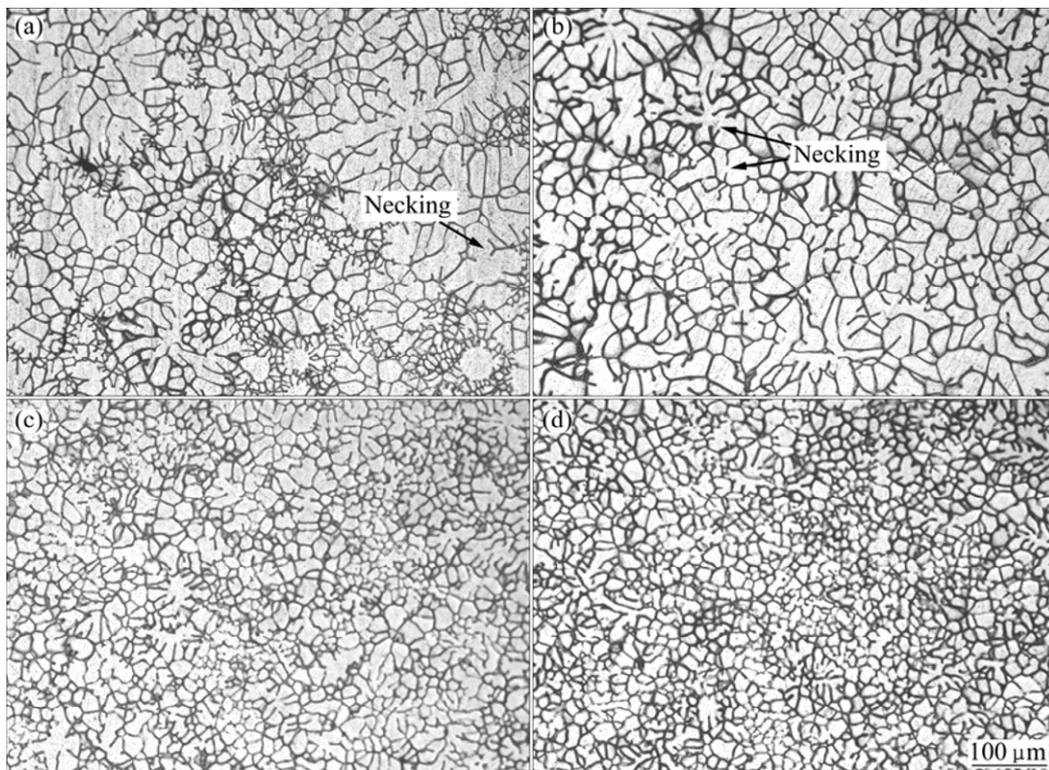


Fig. 2 Microstructures of quenched melt at different positions of sloping plate when cast at 650 °C (corresponding to positions *A*, *B*, *C* and *D* in Fig. 1): (a) Position *A*; (b) Position *B*; (c) Position *C*; (d) Position *D*

nucleus formation was related to two actions, i.e., the strong cooling ability of the sloping plate and the stirrings by metal flow and vibration. In order to analyze the microstructure formation mechanism, the features of the temperature and the flow velocity boundary layers during the process must be investigated firstly. As we all know, there exists metal flow velocity boundary layer (δ) near the plate surface and temperature boundary layer (δ_t) during the process. The thicknesses of the two layers followed by the following relationship [13]:

$$\delta_t = \frac{\delta}{Pr^{1/3}} \quad (1)$$

where Pr is the Prandtl number. The Prandtl number of liquid metal is 0.004–0.029, so the thickness of temperature boundary layer is much larger than that of the velocity boundary layer. There is only a tiny velocity boundary layer near the plate surface, while the temperature boundary layer distributes almost in the entire alloy, which is favorable for nucleation in the melt far from the sloping plate. At the same time, the cooling plate can provide a strong cooling rate. It can be calculated by the convection heat transfer formula that the cooling rate of the melt on the plate surface can reach 1000 K/s which is much larger than 100 K/s for conventional casting process [13]. In this way, homogenous undercooling can be realized in most part of the melt near the plate during the vibrating sloping plate processing, which is favorable for eruptive nucleation in the whole melt on the plate surface, as shown in Fig. 3. Besides the homogenous nucleation, heterogenous nucleation appeared on the sloping plate surface takes place in the melt. Under the flow and vibration, the nuclei forming on the plate surface can disperse into the whole melt. This greatly enhances the quantity of the effective nucleus and eruptive nucleation, eventually promotes the formation of fine and spherical solid structure.

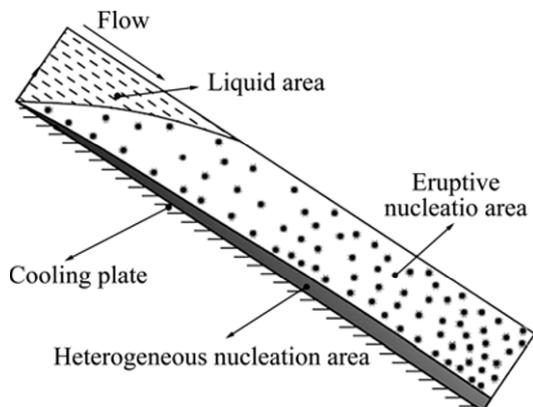


Fig. 3 Schematic diagram of nucleation mechanisms

In addition, it has been found that the primary grain could grow directly with a globular pattern [14], which can also be found in some areas in Fig. 2. However, it is worth noticing that the happening conditions for this behavior are quite different. Direct globular growth is generally considered to take place under the condition that the melt is subjected to shearing action, e.g., twin-screw stirring process [15], shear cooling roll (SCR) process [16]. However, in the current studies, it is found that the direct globular growth still exists in other processes with the absence of a strong shearing. So, the reason that causes direct globular growth is not shearing force, solute and temperature distribution as well as nucleation rate are the essential reasons that determine the grain growth pattern. Besides the direct globular growth pattern, dendrite growth and breakage were also observed. Since A2017 alloy contains high level Cu elements, the aggregation of low melting point solute at dendritic arm root which may neck down under heat flux can take place easily, and this behavior can be observed in Fig. 2. The vibration and metal flow accelerate the dendritic arm to break. Dendritic arm fragments can grow further and evolve into spherical grains.

During the rolling process, the semisolid slurry prepared by the vibrating sloping plate device directly enters into the rectangular closed gap formed by the convex and concave rolls, and under the action of the effective friction force, the slurry in the closed gap is forced to flow, and the rheo-rolling process is achieved. The microstructures of the solidified melt in the roll gap are shown in Fig. 4. Under strong cooling provided by the water-cooling rolls, the primary grains grew further, and most of grains were elongated in the roll gap, as shown in Fig. 4.

The microstructures of A2017 alloy strip at different casting temperatures are shown in Fig. 5. It was found that the plastic deformation along the rolling direction happened obviously. When the casting temperature ranged from 660 °C to 680 °C, the average grain size increased with the increment of the casting temperature. As mentioned above, heterogeneous nucleation and eruptive nucleation on the sloping plate are the main reasons of fine microstructure formation. Heterogeneous nucleation and eruptive nucleation on the sloping plate are tightly related to casting temperature. Generally, nucleation rate increases with the decrease of casting temperature. Therefore, the grain size of the strip also decreases with the decrease of casting temperature.

When the casting temperature was 680 °C, because of high temperature, the solid fraction was low, and there was much remnant liquid in the alloy slurry. Under strong

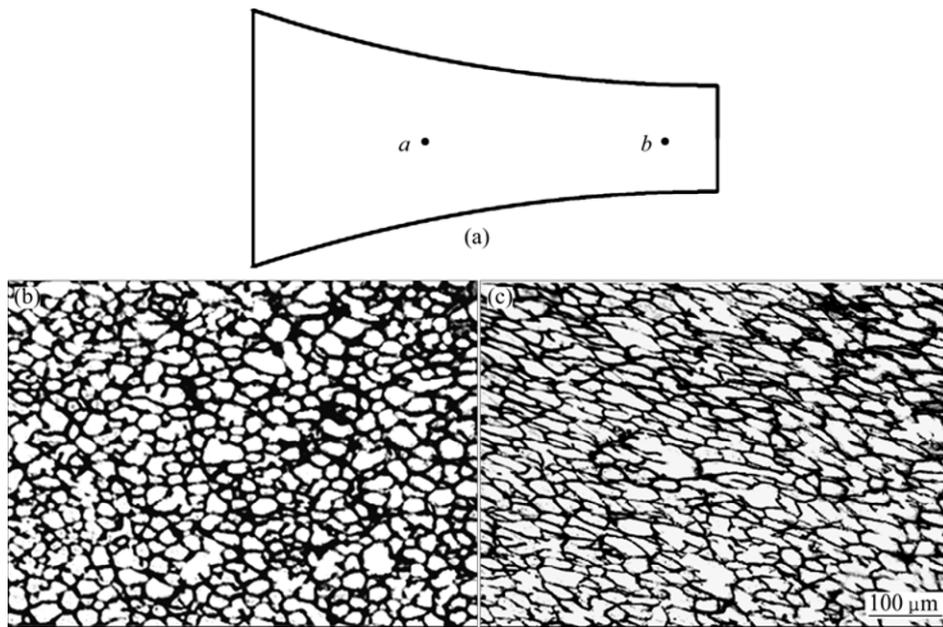


Fig. 4 Specimen locations (a) and microstructures (b, c) of alloy in roll gap when casting at 650 °C: (b) Position *a*; (c) Position *b*

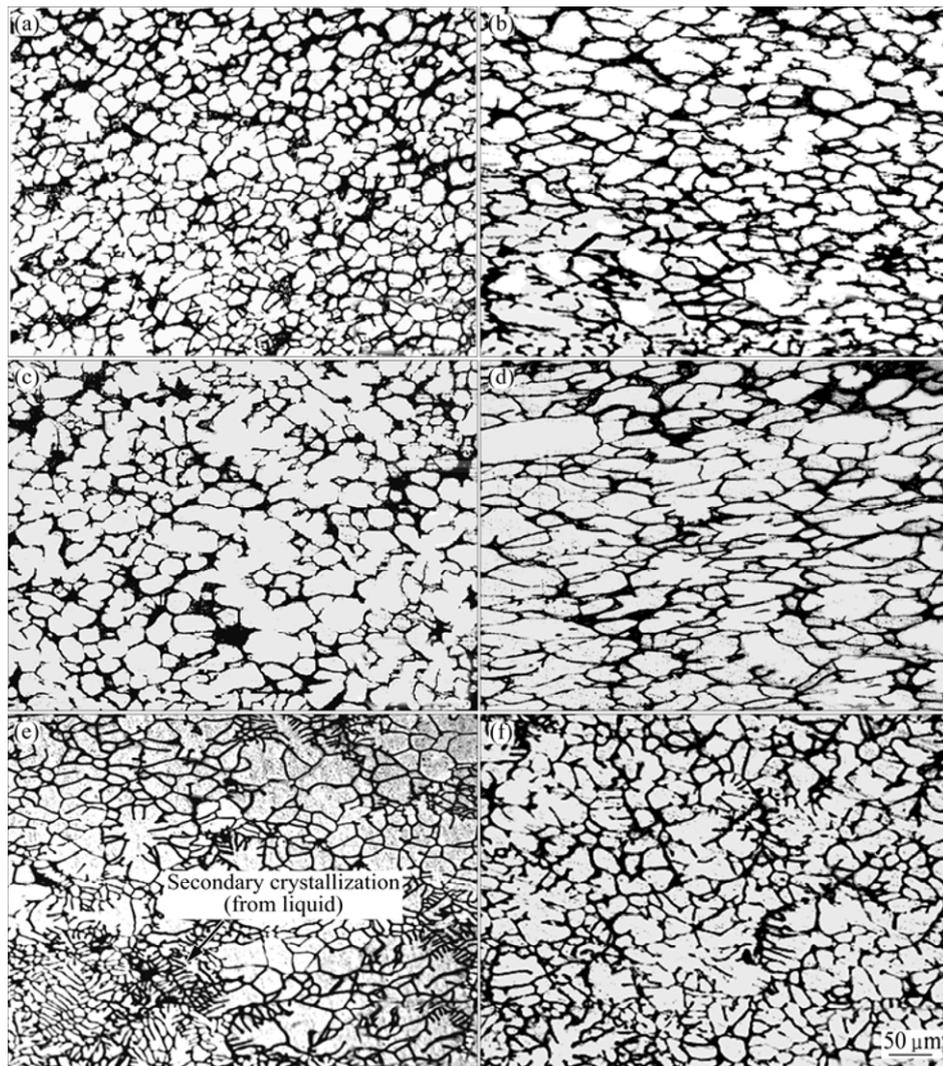


Fig. 5 Microstructures of strips under different cast temperatures: (a) Cross section, 660 °C; (b) Longitudinal section, 660 °C; (c) Cross section, 670 °C; (d) Longitudinal section, 670 °C; (e) Cross section, 680 °C; (f) Longitudinal section, 680 °C

cooling condition provided by the water-cooling rolls, the melt can obtain undercooling during the rolling process, the secondary crystallization of the remnant liquids occurred in the roll gap, and a part of the liquid alloy transformed into the fine grain. However, there are obvious dendrites, as shown in Figs. 5(d) and (e). The large dendrites were mainly formed from the primary grains. The reason is that the nucleation rate on the sloping plate was very small, liquid fraction was too high, and the cooling and shearing time of the rollers on the melt is short in the roll gap, so the dendrites could be found in the strip. Under the current experimental conditions, the casting temperature set from 650 °C to 660 °C is suitable for A2017 alloy.

3.2 Microstructure of A2017 alloy strip produced by proposed process

When the casting temperature exceeded 660 °C, the crack on the surface of the strip occurred, as shown in Fig. 6. When the casting temperature was under 650 °C, the slurry with high solid fraction usually blocked filling mouth of the roll gap, as shown in Fig. 7. Only when the casting temperature was between 650 °C and 660 °C, the A2017 alloy strip could be successfully produced by the current process, as shown in Fig. 8. The microstructure of A2017 strips was mainly composed of fine spherical or rosette grains, as shown in Fig. 8.



Fig. 6 Strip at casting temperature of 680 °C

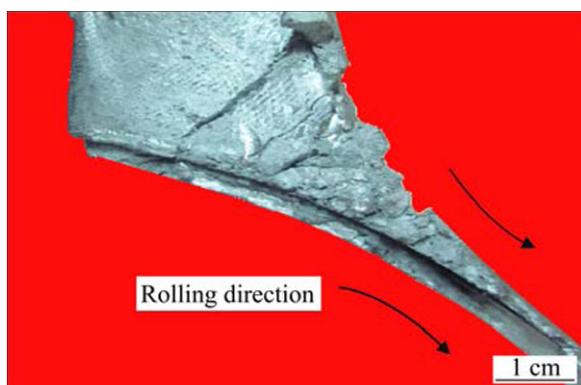


Fig. 7 Stack of metal and gap block at casting temperature of 640 °C

4 Conclusions

1) A novel semisolid rheo-rolling process of A2017

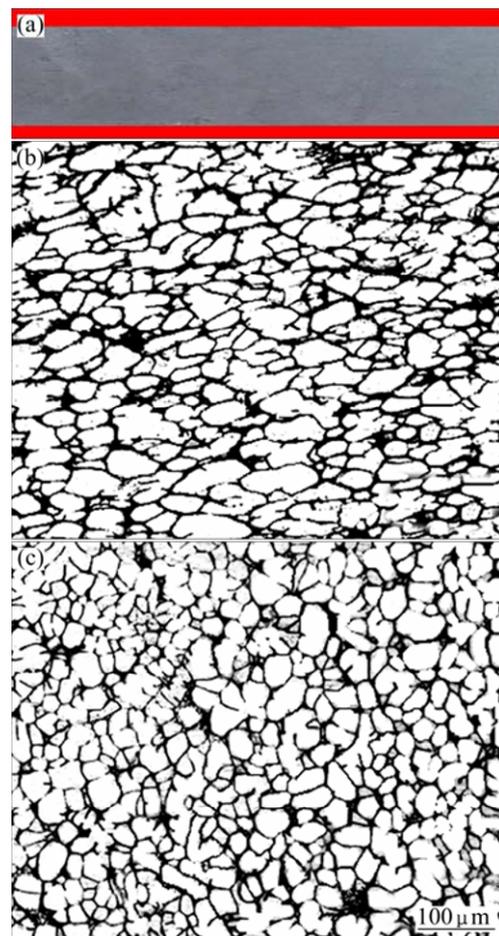


Fig. 8 A2017 alloy strip and its microstructures obtained with optimized parameters cast at 650 °C: (a) A2017 alloy strip; (b) Microstructure of product on longitudinal section; (c) Microstructure of product on cross section

alloy was achieved by combining the shape rolling mill with the vibrating sloping plate device.

2) The high cooling rate caused by the sloping plate and stirring action caused by the vibration and metal flow lead to a high nucleation rate as well as two primary grain growth patterns, direct globular growth as well as dendrite growth and subsequent breakage, which causes the formation of fine spherical or rosette primary grains. During the rolling process, the solid grains of the slurry are elongated.

3) The primary grain size of A2017 alloy strip increases with the increase of casting temperature. When the casting temperature is between 650 °C and 660 °C, A2017 alloy strip with good quality is produced by the proposed process. The microstructures of the strip are mainly composed of fine spherical or rosette grains.

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剪切/振动耦合作用下连续流变轧制成形 A2017 合金组织演化及动态凝固

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摘要: 将振动倾斜板制浆技术与轧制技术有机结合, 开发新型连续流变轧制成形技术, 利用该技术制备 A2017 合金板材。研究连续流变轧制成形过程中 A2017 合金组织演化及动态凝固行为。结果表明, 在振动倾斜板制浆过程中, 由于倾斜板的强冷却及振动作用, 熔体内部形核率较高, 晶粒有两种长大方式: 一是直接球形长大, 二是先枝晶生长然后断裂球化, 因此促进了球形晶和玫瑰晶的形成。在半固态浆料轧制过程中晶粒被拉长。随着浇注温度升高, 晶粒尺寸逐渐变大。当浇注温度为 650–660 °C 时, 可以制备表面形貌和内部组织较好的 A2017 合金板材, 其内部组织主要由球形晶和玫瑰晶组成。

关键词: A2017 合金; 半固态; 倾斜板; 轧制; 组织; 组织演化; 凝固

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