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ARCHIVES
of
FOUNDRY ENGINEERING

10.24425/afe.2019.127123

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

ISSN (2299-2944)
Volume 19
Issue 2/2019

97 – 100

17/2

Effect of Process Parameters on Exudation Thickness in Continuous Unidirectional Solidification Tin Bronze Alloy

Jihui Luo [a], Fang He [b, *]
[a] Yangtze Normal University, China
[b] School of Robot Engineering, Yangtze Normal University, China
* Corresponding author. E-mail address: 903380717@qq.com

Received 15.01.2019; accepted in revised form 21.05.2019

Abstract

The exudation layer seriously affects the properties and the surface finish of the tin bronze alloy. The effective control of the exudation thickness is important measure for improving the properties of the alloy. In order to study the influence of process parameters on the thickness of exudate layer, the tin bronze alloy was prepared by continuous unidirectional solidification technology at different process parameters. The microstructure of the continuous unidirectional solidification tin bronze alloy was analyzed. The effect of process parameters on microstructure and chemical compositions was studied by orthogonal experiment. The results show that there exists an exudation layer on the surface of the continuous unidirectional solidification tin bronze alloy, and the exudation is mainly composed of a tin-rich precipitated phase. It indicates that the continuous casting speed is the main factor affecting the thickness of exudation layer, followed by mold temperature, melt temperature, cooling water temperature and cooling distance.

Keywords: Continuous unidirectional solidification, Tin bronze alloy, Orthogonal experiment, Exudation

1. Introduction

The Tin bronze alloy has a wide solid-liquid two-phase region. When the alloy solidifies, the solute Sn precipitates from the solid dendrite to the liquid phase between the dendrites due to the solute redistribution, causing a serious problem of dendrite segregation [1, 2]. Martorano et al [3] studied the segregation of tin bronze alloy and built the relation between the segregation and dendrite distance. Furthermore, the difference in segregation between the columnar dendrite and the equiaxed dendrite was analyzed, and it was found that there was a large segregation in the equiaxed dendrite region. Kumoto et al [4] investigated the segregation behavior of tin bronze alloy under different cooling rate. The results show that the segregation degree of alloy increases with the increase of the cooling rate.

While precipitated Sn solute enriched at grain boundary of the alloy, grain boundary segregation is formed, resulting in tin bronze alloy containing higher Sn solute at grain boundaries [5]. While precipitated Sn solute is pushed to the center of the alloy by moved solid-liquid interface, positive segregation is formed due to the central of the alloy solidified at the final stage, resulting in a large amount of segregation behavior in the central of the alloy. Therefore, as cast tin bronze alloy generally needs to be homogenized and annealed [6], but the effect is not obvious. In order to improve the uniformity of Sn solute distribution in tin bronze alloy, the method of rapid solidification is widely used in industry [7]. Supersaturated α-phase can be formed in rapid solidification of tin bronze alloy. With the increase of cooling rate, the solidification time is shortened, the solute trapping is correspondingly enhanced, and the Sn solute is too late to precipitate into the liquid phase.

In addition, the tin bronze alloy is also prone to reverse segregation, which is a typical alloy with reverse segregation phenomenon. While the precipitated Sn solute is enriched on the surface of the alloy, the exudation layer is formed. The exudation seriously affects the properties of the alloy [8-11]. Therefore, the effective control of the exudation thickness on the alloy surface is important measure for improving the properties of the alloy. In this paper, tin bronze alloy with diameter of 10 mm was fabricated by continuous unidirectional solidification (CUS) technology. Microstructure of CUS tin bronze alloy was studied by optical microscope (OM) and field emission scanning electron microscopy (SEM). Orthogonal experiment was designed to analyze the effect of process parameters on exudation thickness.

2. Experimental

2.1. Alloy

The material used for this experiment is tin bronze. The composition of the alloy is 6.5% (weight percentage – wt%) of Sn, and the remainder is Cu. The liquidus temperature of the alloy is 1050 °C and solidus temperature is 950 °C.

2.2. Continuous unidirectional solidification

The experiments were performed using the CUS technology. The method and technology for alloy fabrication were described in elsewhere [12]. According to experimental, the melt temperature, mold temperature, continuous casting speed, cooling water temperature, and cooling distance are selected as the main process parameters for $L_{16}(4^5)$ orthogonal experiment design, as shown in Table 1.

Table 1.
Design of orthogonal experiments for CUS tin bronze alloy

Process parameters	Level 1	Level 2	Level 3	Level 4
Melt temperature (°C)	1090	1130	1170	1210
Mold temperature (°C)	1000	1015	1030	1045
Continuous casting speed (mm·min^{-1})	6	16	26	36
Cooling water temperature (°C)	18	22	26	30
Cooling distance (mm)	4	8	12	16

2.3. Microstructures

Samples for microstructure observation were cut from the CUS tin bronze alloy. After polishing, the samples were etched by a solution of $FeCl_3$ (5 g) and alcohol (80 ml). OM and SEM were used to observe the microstructure.

3. Results and Discussion

3.1. Microstructure and composition

Taking the microstructure of No. 3 sample for example, Figure 1a shows its longitudinal microstructure, which exudation can be found in the edge of sample. The composition of exudation was analyzed by EDS. The results show that the Sn content is 30.85 wt% and the Cu content is 69.15 wt%, as shown in Figure 1b, indicating that there was severe Sn segregation on the surface of the alloy. Figure 1(c) shows the SEM of sample, which is subjected to chemical composition analysis using EDS. The scanning area is rectangular, and the arrow in Figure 1(c) indicates the direction from edge to center of the sample. Figure 1d is result of relation between Sn contents and distance from alloy surface. It can be seen that Sn content reaches to 29.10 wt% at the edge of alloy. At about 110 μm from the alloy surface, Sn content decreases to 5.48 wt%. The SEM morphology in Figure 1(d) is an enlarged view of area A in Figure 1(c), and the curve relationship in the blue line frame represents the Sn content value corresponding to each point in the SEM.

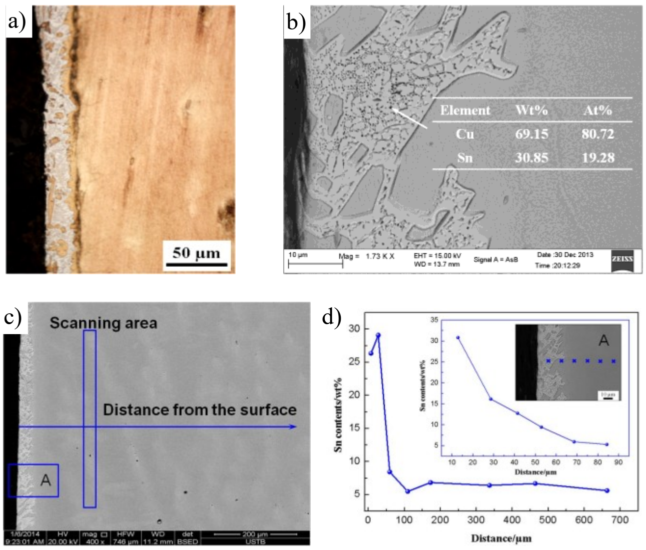

Fig. 1. Microstructures of CUS tin bronze alloy and composition, a) OM, b) c) SEM, d) Chemical compositions

3.2. Effect of process parameters on exudation

Figure 2 shows all the cross-sectional microstructures of the CUS tin bronze alloy with different process parameters in Table 1. It can be seen that the exudation thickness is not the same. The exudate thickness in the figure was measured at three different locations, and the average values of each No were calculated as shown in Table 2. K_i is the average value of result for certain processing parameter, R is defined as the range between the maximum and minimum value of K_i and is used for evaluating the importance of the factors. Compared with the range values of different process parameters, the levels of significance are as follows: continuous casting speed, mold temperature, melt temperature, cooling water temperature and cooling distance.

From the results, it can be found that the exudation thickness is decrease with continuous casting speed increasing. For example, while the continuous casting speed is 35 mm·min^{-1}, the exudation thickness is in the range of 1~18 μm. However, while the casting speed is 5 mm·min^{-1}, the exudation thickness is in the range of 29~42 μm, which increases significantly. In the CUS process, the narrow gap is formed between the mold wall and the edge of solidified alloy [12], which is the main reason that caused the exudation occurring. Increasing of continuous casting speed will cause the solid-liquid interface of the alloy to move downwards. Therefore, the narrow gap between the alloy and the mold begin to disappearing and there is no molten metal that enrichment of Sn solute within the gap. Finally, for the reason of increasing the continuous casting speed, the solidification rate of the alloy is accelerated, which results to Sn solute is too late to precipitate.

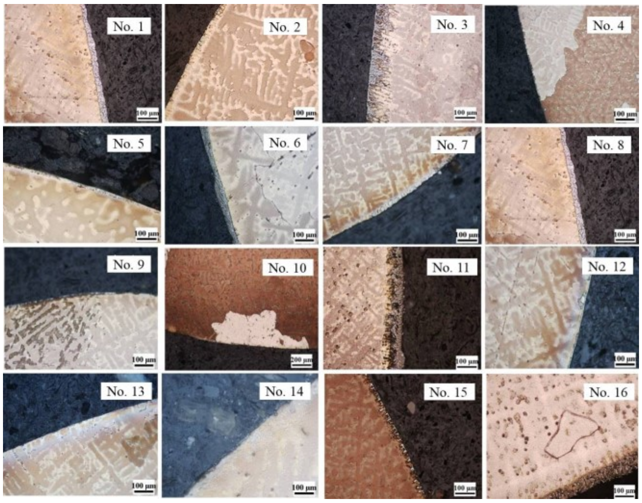

Fig. 2. Microstructures of CUS tin bronze alloy at different process parameters

Table 2.
Results of orthogonal experiments

Nos.	Melt temperature (°C)	Mold temperature (°C)	Continuous casting speed (mm·min^{-1})	Cooling water temperature (°C)	Cooling distance (mm)	Exudation thickness (μm)
1	1090	1000	6	18	4	35.08
2	1090	1015	16	22	8	24.12
3	1090	1030	26	26	12	47.86
4	1090	1045	36	30	16	4.02
5	1130	1000	16	26	16	6.16
6	1130	1015	6	30	12	29.24
7	1130	1030	36	18	8	18.14
8	1130	1045	26	22	4	21.04
9	1170	1000	26	30	8	7.06
10	1170	1015	36	26	4	1.02
11	1170	1030	6	22	16	42.58
12	1170	1045	16	18	12	6.42
13	1210	1000	36	22	12	4.12
14	1210	1015	26	18	16	2.34
15	1210	1030	16	30	4	11.14
16	1210	1045	6	26	8	41.22
K_i (average value of result for certain processing parameter) i standard level in Table 1, i={1,2,3,4}, and R (range between the maximum and minimum value of K_i averages), μm						
K_1	27.77	13.11	37.03	15.50	17.07	
K_2	18.65	14.18	11.96	22.97	22.64	
K_3	14.27	29.93	19.58	24.07	21.91	
K_4	14.71	18.18	6.83	12.87	13.78	
R	13.50	16.82	30.21	11.20	8.86	

4. Conclusions

The tin bronze alloy was prepared by CUS process. The effect of process parameters on microstructure of CUS tin bronze alloy was studied. The following conclusions can be drawn:

1) There exists a exudation layer on the edge of the CUS tin bronze alloy. The exudation layer mainly consists of a tin-rich phase.
2) The orthogonal test results showed that the effect of continuous casting speed is more dominant than other

factors, the secondary factors are mold temperature, melt temperature, cooling water temperature and cooling distance in turn.

Acknowledgements

This work was supported by the project of Yangtze Normal University No. 2017KYQD130.

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