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Cavitation erosion mechanism of titanium alloy radiation rods in aluminum melt

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ABSTRACT

Ultrasound radiation rods play a key role in introducing ultrasonic to the grain refinement of large-size cast aluminum ingots (with diameter over 800 mm), but the severe cavitation corrosion of radiation rods limit the wide application of ultrasonic in the metallurgy field. In this paper, the cavitation erosion of Ti alloy radiation rod (TARR) in the semi-continuous direct-chill casting of 7050 Al alloy was investigated using a 20 kHz ultrasonic vibrator. The macro/micro characterization of Ti alloy was performed using an optical digital microscopy and a scanning electron microscopy, respectively. The results indicated that the cavitation erosion and the chemical reaction play different roles throughout different corrosion periods. Meanwhile, the relationship between mass-loss and time during cavitation erosion was measured and analyzed. According to the rate of mass-loss to time, the whole cavitation erosion process was divided into four individual periods and the mechanism in each period was studied accordingly.

1. Introduction

The ultrasonic treatment of light alloy melts has been studied over half a century and was used in semi-continuous casting of ingots with 800–1200 mm in diameter and up to 6000 mm in length. In metal melts, the ultrasonic with high frequencies can induce some nonlinear effects, including the cavitation, acoustic streaming, mechanical shock and radiation pressure [1–3]. Besides, it has been found that the ultrasonic effectively reduces the macro/micro segregation and promotes the columnar-to-equiaxed transition (CET) in casting [4–6]. In this process, the ultrasonic radiation rods are an essential working medium to introduce ultrasonic waves into metal melts. However, the ultrasonic radiation rods are easy to be damaged by cavitation erosion [7], limiting its service life. So finding a material with resistance to high temperature corrosion under ultrasonic treatment is essential.

An ideal material for the radiation rods should satisfy the following requirements: (a) high melting point, (b) good fatigue resistance, (c) low solubility in liquid metal, (d) strong resistance to cavitation erosion, and (e) small thermal expansion coefficient [8]. Numerous experiments with different materials revealed, however, that it is hard to find a candidate to meet all the requirements. Currently, only metallic materials can satisfy these requirements to a practical extent. Pioneering experimental studies on cavitation stability of various metals in Al melts were performed in the 1960s. All of studied materials suffer from dissolution and erosion, Nb appears to be the most stable [8]. For instance, as a radiation rod, the Nb–4 wt.% Mo alloys (VN2, GOST Standards, Russia) can work 40 h or more for the cavitation treatment of molten Al alloys [7]. Moreover, the Nb–Mo–Zr alloys (C103-type) can remain stable for 300 h in Al melt. It is a pity that they cannot effectively transfer ultrasonic due to their poor acoustic characteristics [8]. In addition, the exorbitant price limits the scope of applications. Generally speaking, the corrosion-resistance of Ti alloy is slightly weaker than that of Nb alloy. However, as a common element in commercial Al alloys, the Ti alloy has a good combination of acoustic properties, thermal stability, low density, and low thermal conductivity [8]. Moreover, the low price makes Ti alloy easier to be used as the radiation rod in ultrasonic treatment of light alloy melts. A new homemade Ti alloy radiation rod (TARR) was found to be able to work in the Al melt at high temperature for a long time. This confidential TARR has the advantages of good compatibility and excellent corrosion resistance.

Ti alloys are applied more broadly to make of ultrasonic radiation rod for the cavitation treatment of molten Al alloys. However, data on the performance of such radiation rod is lacking in the

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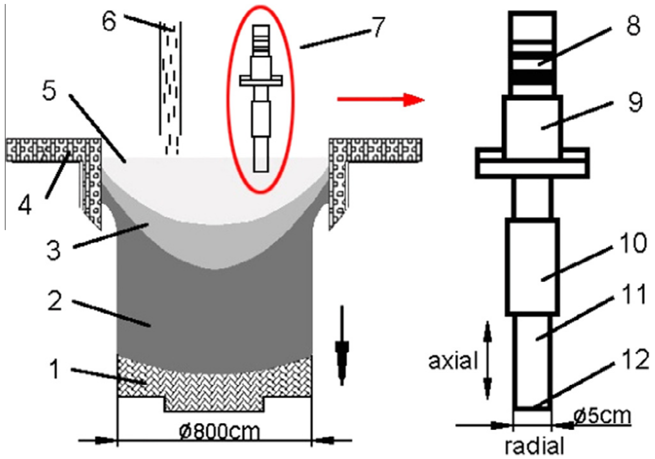

Fig. 1. Schematic illustration of the apparatus for corrosion experiments: 1-dummy plate, 2-solid ingot, 3-mushy zone, 4-crystallizer, 5-liquid zone, 6-liquid metal, 7-ultrasonic vibration system, 8-piezoelectric ceramic, 9-transducer, 10-transformering rod, 11-TARR, and 12-radiation rod tip (sample surface).

literature. Scientific literature [8] mentioned that the materials properties of Ti alloy and experimental research of Ti alloy radiation rods, but many important details on the characteristics of TARRs were lacking. Theoretically, the formation and collapse of cavitation bubbles near the wall are foundation of the cavitation erosion. Based on the Euler fluid theory, Abdullah et al. [9] simulated the procedure of growth and collapse of cavitation bubbles. Using finite difference method, Kim et al. [10] and Rivas et al. [11] studied the interaction between different cavitation bubbles. Bai et al. [12] and Uemura [13] explored the characteristics of cavitation erosion under ultrasonic field with the aid of high speed photography. In addition, Chiu et al. [14] and Jiang et al. [15] investigated the roughness evolution of the wall that was caused by ultrasonic cavitation, respectively. However, all the theories/mechanisms above were conducted at normal temperature, which cannot fully explain the effect of cavitation erosion on TARRs at high temperature in Al melt.

In this paper, the ultrasonic treatment was applied to the semi-continuous casting of large-sized Al ingot (800 mm in diameter) through a TARR. Then, the corrosion behavior and micro structural evolution of TARR were obtained by scanning electron microscopy (SEM) and the optical digital microscope. The ratio of time to mass loss for a TARR at typical stages of the corrosion process was determined, which would clearly grasp the characteristics of corrosion resistance. Furthermore, the cavitation erosion mechanisms of the TARR in large Al ingots were investigated. This paper can provide an insight to develop TARR with better resistance to cavitation erosion in the ultrasonic melt processing.

2. Experimental

2.1. Materials and devices

Experimental object was the TARR and the auxiliary material was 7050 Al alloy. The experimental devices included a set of ultrasonic vibration system (a PZT piezoelectric ceramic, transducer, transformer rod and a Ti alloy radiation rod sized Φ50 mm × 110 mm), a set of homemade digital ultrasonic generator and a set of assembly casting machine (Fig. 1).

2.2. Experimental procedure

Two experiments, with and without ultrasonic treatment for TARR in Al melt, were compared. In the first experiment, the billet was continuously cast at a rate of 0.3–0.4 mm/s, and the pouring temperature of 7050 Al melt was set to be 700 °C. When the length of billet reached 300 mm, the TARR (labeled as A) was inserted into the melt to a depth of 30 ± 2 mm. The vibratory frequency and the peak-to-peak amplitude were 20 ± 1 kHz and 20 ± 1.0 μm, respectively. The vibratory amplitude was measured using a laser displacement sensor (LK-G5000 Series, KEYENCE®). After completing each 3-h test, the TARR surface was cleaned using dilute nitric acid solution. Then the weight of the TARRs was determined by an analytical balance and the mass loss was recorded. In addition, the morphology and distribution of erosion pits on the TARRs surface were examined by the scanning electron microscope (SEM, TESCAN, MIRA 3 LMH/LMU) and the optical digital microscope (Olympus, DSX500), respectively. After performing these measurements, the TARR was test again in the next 3-h experiment. The total time of testing was 36 h (12 times experiments). In order to investigate in more details, the sample surface was cut along the tip of center line, and the cross section was examined by SEM. In the second experiment, the above experimental procedures were conducted/repeated on the TARR (labeled as B). The difference is that TARR was inserted into the melt without ultrasonic treatment and the total time of testing was just 18 h (6 times experiments).

3. Results

3.1. Mass loss of the TARR

Normally, the relative resistance of a material to the cavitation erosion can be characterized through measuring the mass loss [16]. In the first experiment, the mass loss, which was measured at different times under cavitation erosion, is plotted against the treatment time. Based on the cavitation erosion rate (the slope of the curve), the whole corrosion procedure can be divided into four periods, as shown in Fig. 2. The total mass loss of the TARR is 85.3 g, accounting for 6.6% of the initial mass. In general, there is negligible loss in the mass of TARR at the incubation period of cavitation erosion. In this experiment, the mass loss ratio of TARR is only about 0.63 g/h at the incubation period. At the acceleration period, the corrosion is attributed to the combined effect of both cavitation erosion and chemical reaction, and then the average mass loss rate increases to 1.56 g/h. During the stable period, the increase in the number and size of erosion pits lead to the increasing area of interface between TARR and melt, which further causes that the rate of mass loss reaches its maximum value ($\tan\alpha$ = 5.2 g/

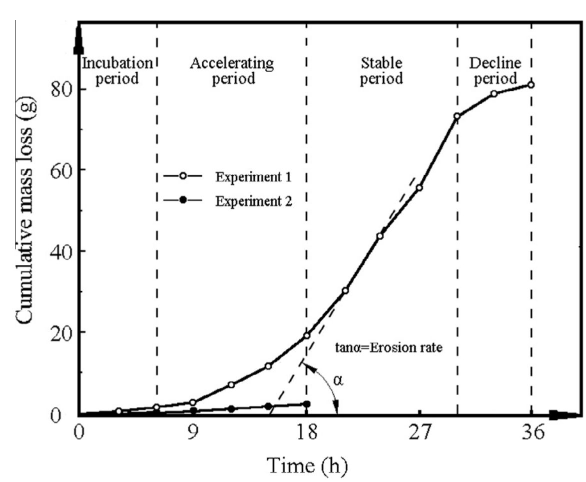

Fig. 2. Cavitation period in cumulative mass loss (material mass loss)–time curve. Slope of the curve in this figure denotes the cavitation erosion rate.