Study on the cavitation range of the side of the ultrasound radiation rod in aluminum melt

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Abstract. The effect of cavitation and sound flow produced by ultrasound in high temperature melt is utilized to achieve grain refinement. Previous papers mainly discussed the cavitation mechanism of the end face of the ultrasonic radiation rod, but did not pay enough attention to the cavitation effect on the side face of the radiation rod. Therefore, this paper studied the cavitation range of the side of the ultrasonic radiation rod. Firstly, the amplitude of the side of the ultrasonic radiation rod was measured. It was found that the amplitude of the side varied greatly with the location. Secondly, the simulation results showed that the vibration of the side of the radiation rod changed alternately with periodic peaks and troughs. Thirdly, the ultrasonic experiment of pure aluminum was carried out in crucible. Two titanium plates were cut into a suitable shape and placed in crucible. After 13.5 hours of ultrasonic treatment, it was found that the surface of titanium plates was not uniformly eroded, but the most serious cavitation erosion occurred in the middle position. Therefore, it can be explained that the cavitation effect occurred in this region. At the same time, the macrostructure of aluminium ingot treated by ultrasound was obviously refined.

1. Introduction

Ultrasound has many unique advantages, so it can be used in many fields. In recent years, more and more attention has been paid to the application of ultrasonic in the field of light alloy casting. For example, ultrasonic wave was applied to aluminum alloy casting [1,2] and magnesium alloy casting [3]. G.I. Eskin et al. [1] studies shown that the ultrasonic cavitation treatment combined with microalloying of hypereutectic Al-Si natural composites (alloys) promoted the formation of structures suitable for further deformation. In the literature [2], experimental result confirmed that a globular/non-dendritic microstructure could be effectively obtained when the melt was ultrasonically treated. Han-song XUE et al. [3] studies shown when the ultrasonic treatment power was 700 W, the best comprehensive mechanical properties of Mg-6Zn-0.5Y-2Sn alloy were obtained. And ultrasonic cavitation treatment helped to overcome the difficulties of the introduction of the elements (Pb,Bi,Sn,etc) into an aluminum melt, and increased the solubility of solute elements, therefore, the properties of aluminum alloy ingot had been improved [4].

The collapse of the cavitation bubble caused by the ultrasonic wave, the energy of the collapse was transformed into pressure pulses up to 1000 MPa and into cumulative jets up to 100 m/s [4]. The use of cavitation in melt treatment provided a rapid diffusion growth of bubble nuclei, thereby the degassing
effect was accelerated. Meanwhile, G.I. Eskin studies showed that ultrasonic cavitation treatment could produce a principally new structural type called “non-dendritic”. The effect of ultrasonic can not only refine the grain of ingot, but also reduce the defects of ingot.

Ultrasonic wave in the alloy casting has many advantages, but the ultrasonic radiation rods are very easy to erosion damage in the high temperature melt, which seriously affects the continuous and steady work of ultrasonic wave [5-6]. In the literature [5], the results showed that the Nb-Mo tip had superior resistance to erosion than the Nb one, and showed a longer life span and good property to produce cavitation in an aluminum melt even after 40 hours of ultrasonic irradiation. In the literature [6], the results indicated that the cavitation erosion and the chemical reaction played different roles throughout different erosion periods.

However, the effect area of cavitation has not been systematically discussed. In the literature [7], only the cavitation region at the end of the ultrasonic radiation rod was discussed. In this paper, the cavitation region on the side of the ultrasonic radiation rod will be discussed.

2. Experimental
The experimental equipment includes the following:① Ultrasound power supply can output 12 different grades of power, and the output frequency range of ultrasound is 15 KHz-22 KHz. When the radiating rod acts in molten aluminium, the optimal vibration effect of the radiating rod can be achieved by adjusting the power and frequency of the ultrasonic power supply.② The ultrasonic vibration system consists of a PZT piezoelectric ceramic transducer and a titanium alloy radiating rod. Its function is the generation and transmission of ultrasound.③ The high temperature resistance furnace and its auxiliary equipment can melt the pure aluminum and keep it at the specified temperature by setting its parameters.④ Hydrochloric acid and other corrosive agents were used to remove residual aluminum on the surface of titanium alloy plates.⑤ KEYENCE laser range finder and related auxiliary equipment were used to measure the amplitude of cylindrical surface of ultrasonic radiation rod. ⑥ Keynes Optical Microscope. Keynes Optical Microscope was used to observe the micro-morphology of the eroded titanium alloy plate.

Before the experiment of ultrasonic casting, the amplitude of the radiation rod was measured with the high precision Keyence laser range finder. The diameter and length of the radiation rod were 50 mm and 365 mm, respectively. The 30 measuring points were evenly distributed on the cylindrical surface of the radiation rod, and I, II, III, IV respectively as the starting point. Because I and III, II and IV were axisymmetric, only I and II were used as the starting point, and 30 measuring points were evenly distributed along the surface of the radiation rod in the direction of the parallel axis. The distance between each measurement was 10 mm, and the first point was 10 mm from the end face, as shown in figure 1.

The amplitude of high frequency ultrasonic vibration was micron, so the high precision Keyence laser range finder was used to measure the amplitude of the rod. Amplitude detection equipment was the Japanese KEYENCE LK-G5000 series LK-H020 laser range finder. The maximum acquisition frequency of the model range finder was 392 KHz, the measurement precision was 0.001 um, the data limit obtained for each test was $10^6$. In the experiment of this paper, the vibration frequency of the ultrasonic radiation rod was 20 KHz, each time detection could obtain 65536 amplitude data.
In order to study the cavitation law of the side of the ultrasonic radiation rod, the following experiments were designed. 17.5 kg of pure aluminum was weighed and placed in a graphite crucible, and then the whole graphite crucible was placed in a resistance furnace. The resistance furnace was set at 750 °C. After the pure aluminum melted, the temperature was stable at 700 °C.

The TA2 titanium alloy plate was sheared into a suitable shape for easy insertion into the molten aluminum and could be fixed on the graphite crucible. The composition of the TA2 titanium alloy plate is shown in Table 1. In order to make the results credible, two TA2 titanium alloy plates were inserted into the graphite crucible, and then the ultrasonic radiation rod was inserted into the aluminum melt. The ultrasonic radiation rod parameters were set. The ultrasonic radiation rod frequency was 20 KHz, and the power was 2000±20 W, as shown in figure 2.

| Main component% | Impurities%, aximum | Other elements%, aximum |
|-----------------|---------------------|------------------------|
| Al              | V                   | Ti                     |
| 5.5–6.75        | 3.5–4.5             | Bal.                   |
|                 | C                   | Fe                     |
|                 | 0.08                | 0.05                   |
|                 | N                   | H                      |
|                 | 0.15                | 0.20                   |
|                 | O                   | Single element         |
|                 | 0.1                 | The sum                |
|                 |                     | 0.4                    |

The penetration depth of two titanium alloy plates and the ultrasonic radiation rod into molten aluminum was 170 mm. After vibration of the ultrasonic radiation rod in molten aluminum for 13.5 hours, two titanium alloy plates were taken out, the power supply was turned off, the ultrasonic
vibration system was removed, and then the residual aluminum on the surface of two titanium plates was cleaned with hydrochloric acid after temperature cooling.

3. Results

3.1. Amplitude of the cylindrical surface of the radiation rod

From figure 1, a total of 60 measurement positions were selected from I-1 to I-30, and II-1 to II-30, and 65536 vibration data were obtained at each position. Because of the large amount of data and the similarity of vibration rules, taking the measured positions (I-1), (I-6), (I-12), (I-18), (I-24), (I-30) as examples, the vibration data were transformed into graphs, as shown in figure 3. From figure 3(a), we can see that the measured amplitude fluctuates in the range of -2 um to 1.5 um. At the same time, only a few of the data are less than -2 um or larger than 1.5 um. Therefore, the range of vibration amplitude at position (I-1) is acceptable from -2 um to 1.5 um. From figure 3(b), it can be seen that the range of vibration amplitude is from -3.5 um to 0.5 um, whereas the vibration equilibrium position increases at the abscissa coordinates from 10000 to 20000. figure 3(c) shows that the amplitude ranges from -6.5 um to 0 um. It can be seen from figure 3(d) that the range of amplitude is from -0.5 um to 1.5 um, and the vibration equilibrium position is reduced in the range of abscissa 10000-30000. As can be seen from figure 3(e) and figure 3(f), the range of amplitude fluctuation is -6 um to 1 um and -1.5 um to 2 um, respectively.

From figure 3, it can be seen that the vibration data obtained by measuring the cylindrical surface of an ultrasonic radiation rod have different vibration ranges at different measuring locations, but these vibration data show similar vibration laws, all of which are periodic. The data obtained from each measurement was 65536, so when converted into numerical graphics, the data was too dense, which hindered further analysis and research.

In order to better study these data, the first 128 data obtained from each measurement position were analyzed, and the results were shown in Fig. 4. From figure 4, these vibration data still obeyed the law of periodic vibration. From figure 4(a), 4(b), 4(c), 4(d), 4(e), 4(f), it can be seen that the amplitude
showed periodic fluctuations. Although the shapes of the vibration were different, basically 20 data showed a period. The positions of (I-1), (I-6), (I-24), i.e. figure 4(a), 4(b) and 4(e), showed that the period was very obvious. In (I-18) position, corresponding to figure 4(d), the period was not so obvious, because in this position, the amplitude was small, so the period was not easy to distinguish.

The difference between figure 3 and figure 4 is that the number of data is different. figure 3 is more dense with 65536 data, which can better reflect the vibration law in macro. The data in figure 4 only have 128 data, which can better reflect the law of vibration in micro-level.

From figure 4(a), we can see that the measured amplitude fluctuates in the range of -1.8 um to 0.8 um. From figure 4(b), it can be seen that the vibration amplitude of position point (I-6) ranges from -3.5 um to 0.5 um. figure 4(c) shows that the amplitude ranges from -6.2 um to 0 um. It can be seen from figure 4(d) that the range of amplitude is from -0.2 um to 1.4 um. As can be seen from figure 4(e) and figure 4(f), the range of amplitude fluctuation is -5.3 um to 0.4 um and -0.8 um to 1.5 um, respectively. It can be concluded that the range of vibration amplitude in figure 3 and figure 4 is very close, so it is acceptable to use 128 data to analyze the amplitude.

![Figure 4. Amplitude fluctuation of different measuring points.](image)

The amplitudes (I(1-30) and II(1-30) obtained from 60 measuring positions on the cylindrical surface of the ultrasonic radiation rod were plotted as curves, as shown in figure 5. The vibration data obtained from 60 measuring points were not all converted into the ones shown in figure 3 and figure 4. Only the average amplitude obtained at each measuring position was plotted as shown in figure 5.
From figure 5, it can be seen that the vibration amplitude of the ultrasonic radiation rod was different at different positions on the side. The distance between each measuring point was 10 mm, and the depth of the ultrasonic radiation rod inserted into the molten aluminum was 170 mm. Therefore, the vibration of the radiation rod in the molten aluminum can be approximated according to the first 17 amplitudes in figure 5.

From figure 5, the position of abscissa 17 had been marked to indicate the demarcation line of the ultrasonic radiation rod inserted into the molten aluminium. The insertion depth of the radiation rod was 170 mm, which corresponded to the first 17 amplitude data. Therefore, we can focus on the first 17 amplitude data. By comparing these amplitude data, it can be found that the data in circles were relatively large amplitude locations. Where the vibration amplitude of the side of the radiation rod was larger, the possibility of cavitation would be greater.

3.2. Simulation Analysis of Ultrasound Radiation Rod

The three-dimensional model of the ultrasonic radiation rod was saved in proper file format and imported into ANSYS Workbench software. The material of the ultrasonic radiation rod was TC4 titanium alloy[11]. In the software, the physical parameters of TC4 material were inputted, the mesh was divided, the constraints were set, and the displacement load was inputted. Based on the modal characteristics obtained by modal analysis, the harmonic response analysis was carried out, and the overall deformation cloud as shown in figure 6 was obtained.

In order to facilitate observation, the deformation of the ultrasonic radiation rod in the software was exaggerated, and the vibration of the ultrasonic radiation rod in the actual process was micron level. figure 6(a) and figure 6(b) showed the two extreme positions of the vibration of the ultrasonic radiating rod respectively. The alternating changes of wave peaks and troughs can be seen on the cylinder surface of the radiating rod. Where the peak was shown in Fig 6(a), the trough was located in figure 6(b). The top and bottom of the radiation rod in figure 6(a) were peaks, while the top and bottom of figure 6(b) were troughs. The middle position of the radiation rod in figure 6(a) was the trough, while in figure 6(b) it was exactly the peak.

In this experiment, the penetration depth of the ultrasonic radiation rod into the molten aluminum was 170 mm, only the effect of the lower part of the radiation rod on the molten aluminum needed to be considered. In the simulation nephogram, the location of the depth of the ultrasonic radiation rod inserted into the molten aluminum and the location of the larger amplitude on the cylinder surface of the radiation rod were marked, which basically coincided with the larger amplitude position measured in section 3.1.
3.3. Experimental results of cavitation on the side of an ultrasonic radiation rod

After the two titanium alloy plates were continuously acted by ultrasonic radiation rod in the molten aluminum for 13.5 hours, they were taken out and part of the aluminium melt adhering to the titanium alloy plates was removed in time. After the two titanium alloy plates were completely cooled, the residual aluminium alloy on their surfaces was cleaned by hydrochloric acid, and the erosion morphology of the titanium alloy plates was obtained as shown in figure 7.

It could be seen from the figure that there was no uniform erosion on the surface of the two titanium alloy templates from bottom to top, but in the middle of the two titanium plates. This indicated that cavitation erosion occurred on the side of the radiation rod, and the area was shown in the red wire frame. Similar conclusions could be obtained by comparing two titanium alloy templates. The range of cavitation was basically in this region.

By comparing the erosion of two titanium plates in figure 7 (a) and figure 7 (c), it can be seen from the ruler that the erosion was the most serious in the range of 50 mm to 120 mm. In the red wire frame in figure 7(a) and figure 7(c), the surface of the two titanium alloy plates became obviously rough, with undulating and uneven folds. It was clearer from figure 7(c) and figure 7(d). This did not happen above or below the red wire frame. At the same time, this range was generally consistent with the larger range of amplitude in figure 5. This showed that the probability of cavitation was the largest in this range, which was about 70 mm high.

In the area where erosion was serious on the titanium plate, i.e. within the red wire frame in figure 7(a), tiny holes can be seen with the naked eye. The titanium alloy plate was placed under an optical microscope to observe, and figure 8 was obtained. From the figure, we can see that there are some large and small holes in the observation area, and the large holes are close to 1 mm. The holes were
observed only in the areas where the erosion was serious, but not in the areas where the erosion was not serious. Therefore, it is speculated that these holes of different sizes should be caused by ultrasonic cavitation.

3.4. Macrostructure of pure aluminum ingot
Because the macrostructure of pure aluminium was easier to distinguish, pure aluminium was used in this experiment. Two ingots were obtained by applying and not applying ultrasound. From the middle position of aluminium ingot, 20 mm thick aluminium block was cut along the axis, and then the section of aluminium block was grinded to obtain a smooth surface. Then the surface of aluminium block was corroded by the corrosive reagent, and the macrostructure of the section of aluminium block was obtained, as shown in figure 9.

Figure 9. Macrostructure ((a) without ultrasound and (b) with ultrasound).

figure 9 (a) and (b) showed the macro-structure diagrams of aluminium ingots without ultrasound and with ultrasound, respectively. The red box in figure 9 (b) showed the insertion position of the ultrasonic radiation rod. The insertion depth was 170mm. The longitudinal section of aluminium ingot without ultrasonic treatment was obviously coarse grain structure, while the longitudinal section of aluminium ingot treated by ultrasonic treatment had obvious grain refinement effect.

figure 9(b) showed a clear demarcation between the coarse macro-structure and the fine macro-structure, marked by black line. Under the black line, the macrostructure was uniform, and above the black line, the macrostructure was thick. However, compared with the ingot without ultrasound, the macrostructure of the ingot with ultrasound was smaller even in the area above the black line in figure 9 (b). This was because in the solidification process, the slow solidification region would form a cavity region, which weakened the role of ultrasound refining, making the refined grain structure coarsened again with the prolongation of solidification time.

In this experiment, the ultrasonic radiation rod was inserted into the deeper position of the melt to facilitate analysis the active area on the side of the radiation rod. This was also confirmed from the results, and the grain refinement effect by the ultrasonic action was remarkable, whether at the end
face or the side of the radiation rod.

4. Mechanisms of ultrasonic

By measuring the amplitude of the cylindrical surface of radiant rod, it was found that the amplitude of the cylindrical surface was about 3.5 μm. The vibration interval was 2 times the amplitude, i.e. 7μm. Therefore, according to the sound pressure formula (1), it was possible to produce ultrasonic cavitation on the cylindrical surface of radiant rod.

\[ p_A = A_0 \rho L c_L \omega \]  

(1)

In the literature [4], the collapse of cavitation bubbles would produce the pulse pressure up to 1000 MPa, and the micro jet velocity could reach 100 m/s. The pressure formula (2) in the literature [8] can also be calculated to obtain very large pressure values:

\[ p_{WH} = \rho L c_L v:\left(\frac{\rho_S c_S}{\rho L c_L + \rho_S c_S}\right) \]  

(2)

\[ A_0 \] denotes amplitude, \( \rho \) is the density and the \( c \) is the sound speed. The subscripts \( L \) and \( S \) refer to the liquid and the solid, respectively. The letter \( v \) represents the velocity of micro jets at the vertical wall after cavitation bubbles collapse. Therefore, if the cavitation bubble collapses near the radiation rod, it will directly impact the surface of the radiation rod.

In this experiment, 20 KHz ultrasonic wave was applied to the aluminum melt. Ultrasonic wave propagated longitudinal wave and transverse wave in radiation rod [9]. In the process of ultrasonic propagation, radiation rods itself would vibrate at high frequency, and would mainly deform in the form of longitudinal wave mode, torsional wave mode and bending wave mode as shown in figure 10. Therefore, the amplitude of the deformation was different at different positions on the surface of the radiation rod.

High-frequency vibration would lead to radiation rod in different positions of vibration amplitude was different, so the stress and strain would be different. On the surface of the radiation rod, the larger the deformation is, the greater the stress and strain is. At the same time, the greater the probability of cavitation bubble collapse is more intense. Considering the cavitation effect in the aluminum melt, the sound pressure value should be at least 1.1MPa [10]. From Figs. 7 and 8, it can be seen that the cavitation effect also occurs on the side of the radiating rod. In titanium alloy longitudinal wave velocity is 6100m/s, transverse wave velocity is 3120 m/s [11]. According to the formula of wavelength calculation. A quarter of the longitudinal wavelength is 76.25 mm and a half of the transverse wavelength is 78 mm, which is close to the cavitation range of 70 mm in figure 7.

In section 3 of this paper, the amplitude of the cylindrical surface of the ultrasonic radiating rod is measured, the radiating rod is simulated and analyzed, and the experiment of titanium plate in molten aluminium under the action of ultrasound is carried out. The amplitude distribution on the surface of the radiating rod and the simulation results are in good agreement with the experimental results, as shown in figure 11.
The larger amplitude region of the ultrasonic radiation rod

Figure 11. Comparative analysis of results ((a) simulation result; (b) erosion physical drawing; (c) amplitude fluctuation map).

In the previous study of ultrasonic cavitation experiments, the effect of the end of the ultrasonic radiation rod on the molten aluminium was mainly discussed, but the cavitation range of the side did not attract enough attention[6,7,12-14]. Therefore, through the discussion of this experiment, it can be determined that the side of the ultrasonic radiation rod will also produce ultrasonic cavitation phenomenon, which is conducive to grain refinement of aluminium alloy. Therefore, in the process of large-scale aluminium alloy ultrasonic casting[15], the results discussed in this paper are of practical engineering value.

5. Conclusions
(a) According to the surface erosion of titanium alloy plate, it can be seen that the titanium plate is not uniformly eroded, but locally eroded seriously. This shows that there is cavitation in the side of the ultrasonic radiation rod, which causes the erosion of the titanium plate. The strength of cavitation is related to the law of vibration on the side of the radiating rod. If the amplitude of the radiating rod is stronger, the probability of cavitation in this area will be higher, otherwise, the cavitation is not obvious.

(b) Under the experimental conditions in this paper, the cavity range of the side of the ultrasonic radiation rod was about 70 mm, the height range of 50 mm to 120 mm on the titanium plate. This range was close to 1/4 longitudinal wavelength or 1/2 transverse wavelength.

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