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Influence of non-uniform ultrasonic vibration on casting fluidity of liquid aluminum alloy

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Abstract: The application of ultrasonic vibration to the casting process can be realized through mould (die) vibration. However, the resonant vibration of the mould is always accompanied by a non-uniform vibration distribution at different parts, which may induce a complex liquid flow and affect the casting fluidity during the mould filling process. The influence of non-uniform ultrasonic vibration on the fluidity of liquid AlSi9Cu3 alloy was studied by mould vibration with different vibration gradients. It is found that ultrasonic mould vibration can generate two opposite effects on the casting fluidity: the first, ultrasonic cavitation in melt induced by mould vibration promotes the casting fluidity; the second, the non-uniform mould vibration can induce a melt flow toward the weak vibration areas and turbulence there, consequently decreasing the casting fluidity. When the melt flow and turbulence are violent enough to offset the promoting effect of cavitation on fluidity, the ultrasonic vibration will finally induce a resultant decrease of casting fluidity. The decreasing effect is proportional to the vibration gradient.

Keywords: ultrasonic vibration; vibration gradient; aluminum alloy; fluidity

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1 Introduction

In recent decades, many studies have focused on the application of ultrasonic vibration on the casting of alloy. It has been found that the ultrasonic treatment applied to melt in solidification can significantly refine the microstructure and consequently improve the mechanical properties of alloy, especially for non-ferrous alloy. This can be seen in the ultrasonic refined equiaxed α-Al and primary Si phase in AlSi23 alloy [1], the refined α-Al spherical grains and promoted mechanical properties of AlSi9Cu3 alloy [2], as well as the reduced porosity and defect in AlSi7Mg alloy by ultrasonic treatment in low pressure investment castings [3]. At present, it is generally accepted that the refining mechanism of ultrasonic vibration mainly involves the enhanced heterogeneous nucleation and dendrite fragmentation induced by the acoustic cavitation and streaming [4]. Using synchrotron radiation technique, the heterogeneous nucleation promoted by acoustic cavitation was confirmed in situ, and the cavitation induced dendrite fragmentation was also verified [5-7].

Generally, ultrasonic vibration is introduced by inserting the ultrasonic horn directly into the liquid alloy during solidification, which is more suitable to the direct-chill casting process [8]. However, the propagation of ultrasonic in the melt is always accompanied by attenuation, that is, the sound intensity decreases with the increase of the propagation distance. Ultrasonic waves in propagation can induce an elastic vibration of the medium particle. In the elastic vibration process, the medium viscosity and frictional resistance cause part of the ultrasonic energy to convert into heat and is mainly responsible for the ultrasonic attenuation. In addition, the refraction at the interface between mould and melt, as well as the reflection of the cavity wall also could weaken the ultrasonic wave intensity [9, 10]. The weakening of the ultrasonic wave leads to insufficient cavitation effect in melt, and consequently, an insufficient structure refinement effect to the casting in the corresponding parts [2]. Meanwhile, the application of ultrasonic vibration on complex shape castings is difficult, and studies related are few. With the development of high power ultrasonic equipment, the application of ultrasonic vibration to castings can be realized by mould vibration (such as gravity permanent die casting and pressure die casting using a metal mould). During the solidification process, the vibration is transmitted to the melt through the mould vibration. However, the

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mould is more complicated in shape and structure than the simple ultrasonic horn, and its resonant structure needs to be specially designed. In general, the resonant mode of a component depends on its structure (such as the shape and size, etc.). A resonance mode involves resonance frequency and vibration mode. Vibration mode concerns the distribution of vibration direction and intensity. For a mould with a certain size and structure, its resonant vibration is always characterized by inconsistent vibration direction and intensity at different parts of the mould, even more, there forms a non-uniformly distributed spatial vibration gradient. The non-uniform vibration not only may result in various refining effects at different parts, but also may induce complex liquid flow and the consequent change of fluidity and filling performance of casting.

It has been found that a proper mechanical vibration perpendicular to the wall can reduce the flow resistance of fluidity on it, however, excessive violent vibration can excite turbulence and consequently increase the flow resistance significantly [11, 12]. Mechanical vibration has also been proven to break the dendrites, accompanied by enhanced fluidity and mould-filling capacity of casting [13, 14]. In the past, ultrasonic applied on casting, as a form of high frequency wave, was mainly for the grain refinement and rarely concerned with the melt fluidity – a key factor determining the casting properties of complex castings. In order to promote the application of ultrasonic in improving casting properties, in the present work, the influences of non-uniform mould ultrasonic vibration with different vibration gradients on the fluidity of liquid AlSi9Cu3 aluminum alloy were studied. Further, the influence mechanism was disclosed from the two aspects of dendrite fragmentation and acoustic streaming induced by ultrasonic vibration.

2 Experimental procedure

In the present work, an ultrasonic vibration system was used as shown in the schematic diagram in Fig. 1. It is composed of an ultrasonic generator (TL-1200, adjustable power 0–1,200 W), an ultrasonic transducer (Lead zirconate titanate (PZT-8), nominal frequency 24 kHz), a titanium alloy (Ti6Al4V) horn, and a specially designed spiral fluidity test mould (ductile iron ASTM A536 65-45-12). Ultrasonic vibration was applied on the lower half of the mould by a bolted connection with the horn.

In order to make the vibration system work at resonance, the fluidity test mould was specially designed with the simulation help of COMSOL Multiphysics. As a result, the fluidity test mould was designed with a natural resonance frequency of 23,981 Hz, which coincides with the nominal frequency 24,000 Hz of the ultrasonic transducer, as shown in Fig. 2.

Casting alloy AlSi9Cu3 was used for the fluidity test. It was prepared by pure aluminum (99.9wt.%), Al-20wt.% Si, and Al-40wt.% Cu master alloys. Firstly, pure aluminum was melted in a resistance furnace, and then Al-20wt.% Si and Al-40wt.% Cu master alloys were added in turn. After degassing, the alloy melt was heated to 993 K for pouring. The ultrasonic generator was turned on, and given an input power to excite the ultrasonic vibration of the fluidity test mould, and then the liquid AlSi9Cu3 was poured into the mould. Finally, the ultrasonic vibration was turned off when solidification finished. The fluidity was evaluated by measuring the length of the solidified spiral in the alloy sample.

In order to study the influence of ultrasonic vibration modes on the fluidity of aluminum alloy during casting, comparative experimental schemes were designed, as shown in Table 1. Figure 3 shows the two

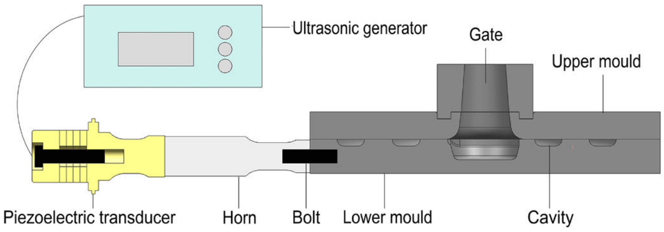


Fig. 1: Schematic diagram of ultrasonic vibration system

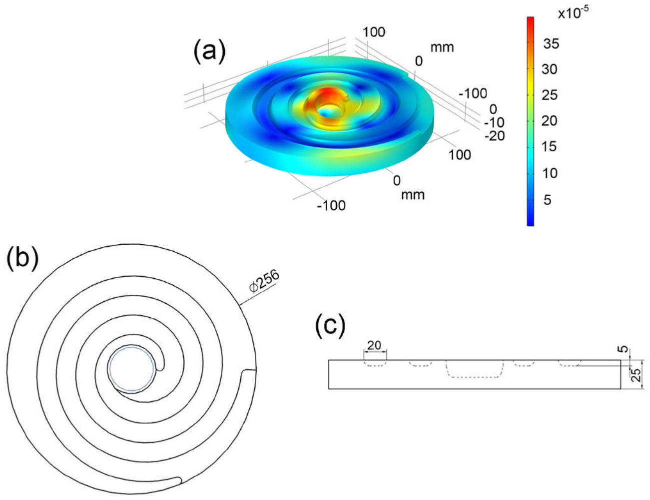


Fig. 2: Spiral fluidity test mould: (a) simulated resonance vibration at frequency 23,981 Hz; (b–c) dimensions of the mould (unit: mm)

Table 1: Schemes for the application of ultrasonic vibration

Schemes	Application mode of ultrasonic vibration	Ultrasonic power (W)
1	No ultrasonic vibration	0
2	Apply ultrasonic vibration on one side of the mould	480
3		720
4		960
5	Apply ultrasonic vibration on both sides of the mould	480 (each side)
6		720 (each side)
7		960 (each side)

application modes of ultrasonic vibration, among which one is to apply the ultrasonic vibration on only one side of the mould (AUOS), and the other is to apply on both sides (AUBS).

For metallurgical examination, the prepared samples were etched by Keller's reagent (2.5% HNO_3+1.5% HCL+1% HF+95% H_2O) after grinding and polishing. The microstructure was analyzed by optical microscopy (Leica DM2700M). The grain size was characterized by the secondary dendrite arm spacing (SDAS). SDAS was obtained on the metallograph by drawing a measuring line across more than five dendrites to calculated the average value of dendrite arm spacing.

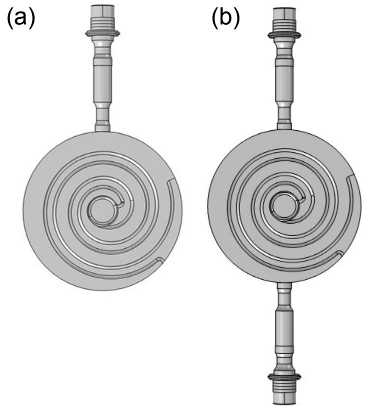


Fig. 3: Application mode of ultrasonic vibration: (a) one side of mould; (b) both sides of mould

3 Results and discussion

3.1 Vibration characteristics of fluidity test mould under AUOS and AUBS modes

The two modes, AUOS and AUBS, defined above are designed to generate different vibration modes for the fluidity test mould, which were simulated by COMSOL Multiphysics. The properties of the material (density, Young's modulus, Poisson's ratio, etc.) required for the calculation are shown in Table 2.

Table 2: Material properties used in numerical models

Materials	Material properties		
	Density ($kg\cdot m^{-3}$)	Young's modulus (GPa)	Poisson's ratio
Structural steel	7,850	200	0.30
Aluminum	2,700	70	0.33
Ti-6Al-4V	4,510	113	0.34
Cast iron	7,000	140	0.25

Figure 4 shows the simulated results of resonance vibrations (23,981 Hz) within the half vibration period. It is shown that both the AUOS and AUBS modes generate non-uniform mould vibration, but the vibration of the mould is more concentrated under AUOS mode than under AUBS mode. The maximum deformation and displacement of the mould under AUOS mode concentrate in the red box area marked in Fig. 4(b). However, the deformation and displacement distribute relatively uniform under the AUBS mode. The larger vibrations are distributed in the two red box areas, as shown in Fig. 4(e). More details can be seen from the cross section shown in Fig. 5, which are sectioned respectively along the Lines A-A and B-B in Fig. 4. It is shown that the mould cavity experiences elastic volume deformation in the half vibration period and the transverse vibrations (in the x-axis and z-axis directions) are more intense than the longitudinal vibrations (in the y-axis direction).

The fluidity of aluminum alloy melt is mainly affected by the vibration of the mould cavity, and not by the vibration of other parts that are not in contact with the melt. So for clarity, only the surface displacements of the cavity were extracted, as shown in Figs. 6(a) and (b). It is shown that the displacement of cavity surface distributes periodically along the spiral under both of the vibration modes. However, the maximum displacement (representing the intensity of vibration) of the cavity surface

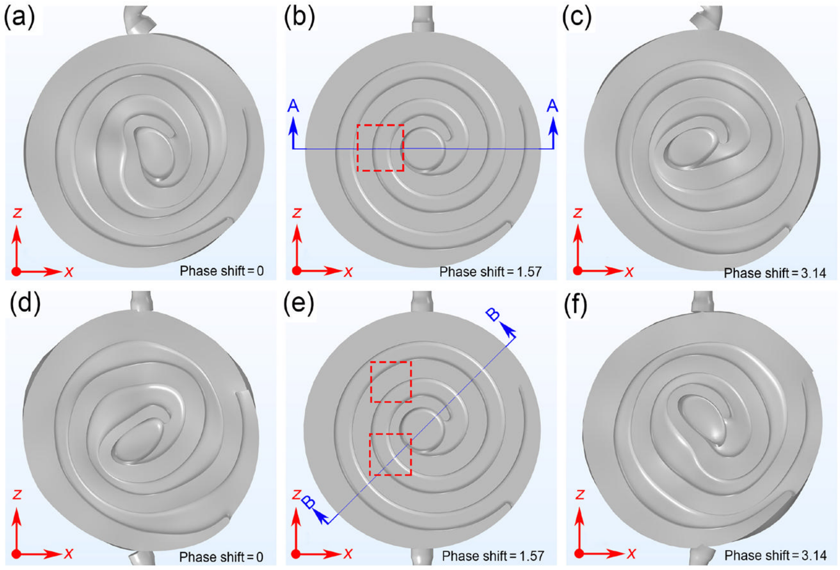


Fig. 4: Simulated resonance vibrations at 23,981 Hz within half period (phase shift from 0 to 3.14) for fluidity test mould in xz-plane: (a–c) vibrations under AUOS mode; (d–f) vibrations under AUBS mode

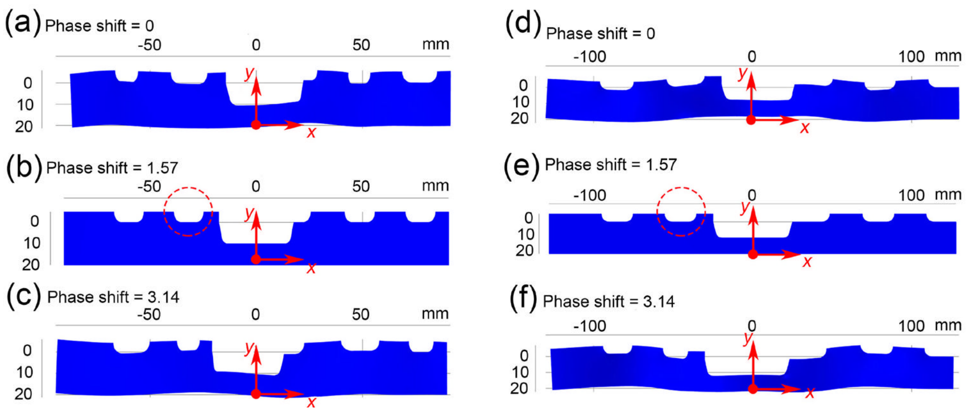


Fig. 5: Simulated resonance vibration within half vibration period (phase shift from 0 to 3.14) for fluidity test mould in *xy*-plane: (a–c) vibration on cross section A-A under AUOS mode; (d–f) vibration on cross section B-B under AUBS mode (cross sections A-A and B-B as marked in Fig. 4)

under the AUOS mode with input power 960 W reaches 32 μm, which is about twice as large as that under the AUBS mode.

The distributions of ceramic sands (particle size of 75 μm) driven by ultrasonic vibration in the mould cavity were used to verify the difference of displacement under the AUOS and AUBS modes with the input ultrasonic power of 960 W. Firstly, the ceramic sands were uniformly distributed in the mould cavity, and then the ultrasonic vibration was turned on to drive the ceramic sands to distribute to a stable distribution state. Forced by the vibration, the ceramic sands flow from the areas with large displacement to the adjacent areas with small displacement, and finally accumulate in the areas with small displacement, as the results shown in Figs. 6(c) and (d). It is shown that the simulated vibration under the AUOS mode in Fig. 6(a) is in good accordance with the actual vibration tested in Fig. 6(c). That is, ceramic sands almost all accumulate in the weak vibration areas, conversely, no sands distribute in the violent vibration areas. However, as shown in Figs. 6(b) and (d), under the AUBS mode, the actual vibration distribution is more uniform than the simulated result. This is attributed to the interference of ultrasonic waves from both sides under the AUBS mode, which also reduces the vibration amplitude. The larger the displacement gradient along the spiral cavity, the more aggregated distribution of the ceramic sands. By comparison, it can be found that the mould vibration along the spiral cavity under the AUOS mode has a higher displacement gradient and is more non-uniform than that under the AUBS mode. It should be stressed that the deviation between the distribution of ceramic sands and the vibration intensity distribution was obtained from the simulation. This is attributed to the vibration system being assembled with a pre-tightening force in the actual test process. During the vibration process, the pre-tightening force will change continuously due to the vibration, which cannot be well-reflected in the simulation. In addition, the mould gravity and the friction between the mould and the working platforms generate certain constraints, which cannot be reflected in the simulation process.

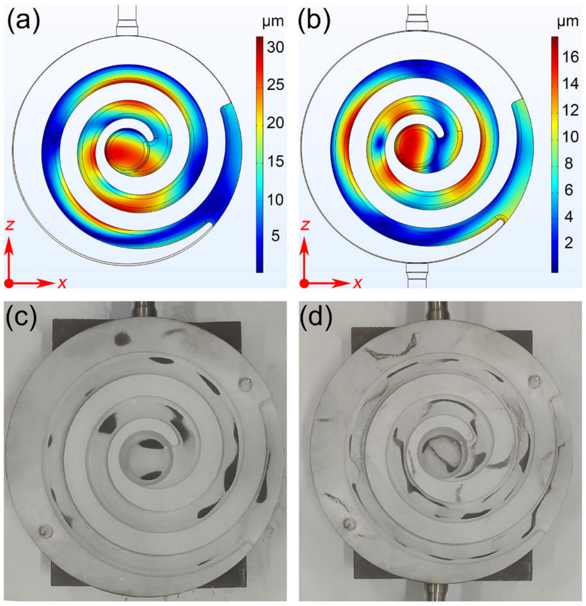


Fig. 6: Vibration of cavity under input ultrasonic power of 960 W: displacement distribution under AUOS (a) and AUBS (b) modes; ceramic sands distribution under AUOS (c) and AUBS (d) modes

To further illustrate the displacement gradient along the spiral cavity, displacement values along the Line A segment from 0 mm to 150 mm were extracted respectively, as shown in Figs. 7(a) and (b). It can be seen that the maximum displacement gradient under the AUOS mode is about 1.9 times the absolute value of that under the AUBS mode. The displacement gradient is proportional to the input ultrasonic power, that is, the higher the input power, the greater the displacement gradient.

3.2 Influence of displacement gradient on melt fluidity

The lengths of spiral AlSi9Cu3 alloy samples obtained through fluidity testing are shown in Fig. 8 and Fig. 9, which are used to represent the fluidity. It is shown that the lengths of spiral samples are lengthened under the AUBS vibration mode, and are proportional to the input ultrasonic power. However, the lengths of spiral samples are shortened under the AUOS vibration mode, and are inversely proportional to the input

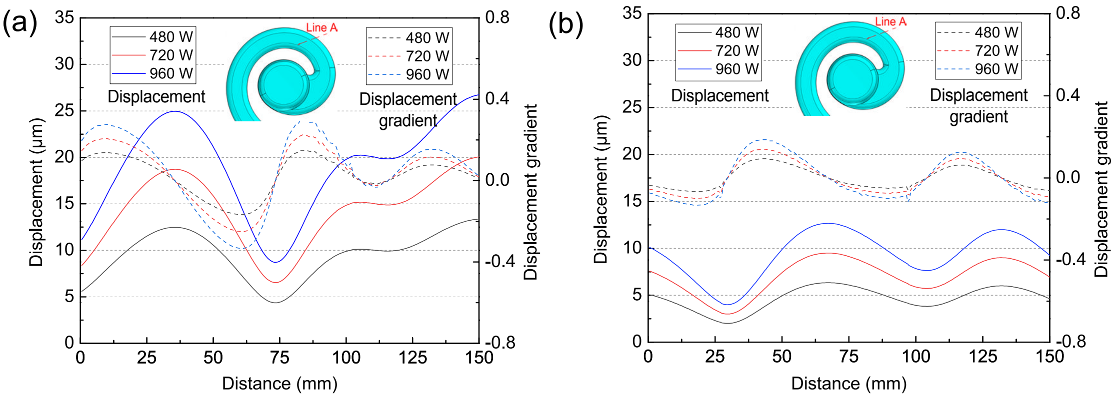


Fig. 7: Displacement gradient along the spiral cavity: (a) AUOS mode; (b) AUBS mode

ultrasonic power. It means that the AUBS mode promotes the casting fluidity of liquid AlSi9Cu3 alloy, but the AUOS mode decreases fluidity. In other words, a relatively uniform mould vibration with small vibration gradient can promote the casting fluidity, however, a non-uniform mould vibration with large vibration gradient does the opposite.

The solidification range of AlSi9Cu3 alloy goes from liquidus 861 K to solidus 781 K, indicating a mushy solidification characteristic. Therefore, the development of primary α(Al) dendrites constructing a network during solidification is an essential inhibitory factor to the casting fluidity. It has been found that ultrasonic vibration could significantly influence the solidification of aluminum alloy [15, 16]. Especially, the acoustic cavitation can break the dendrites during solidification [17, 18]. Although less reported, this dendrite broken effect induced by the cavitation theoretically can also promote the casting fluidity. In addition, the cavitation effect can destroy the alumina film and improve the wetting of melt to substrate, which is also favorable to the fluidity [4]. Those positive effects of ultrasonic vibration on fluidity seem to work under the AUBS mode in the present study. However, even the AUOS mode provides more violent ultrasonic vibration on the mould cavity, it cannot increase the fluidity as expected but decrease.

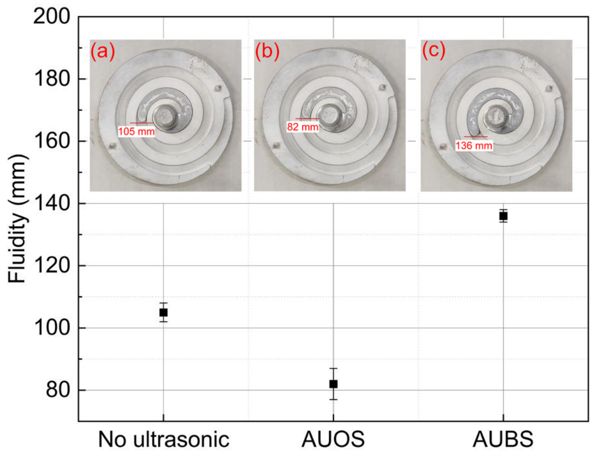


Fig. 8: Influence of ultrasonic application mode on fluidity: (a) without ultrasonic vibration; ultrasonic power of 960 W under AUOS (b) and AUBS (c) modes

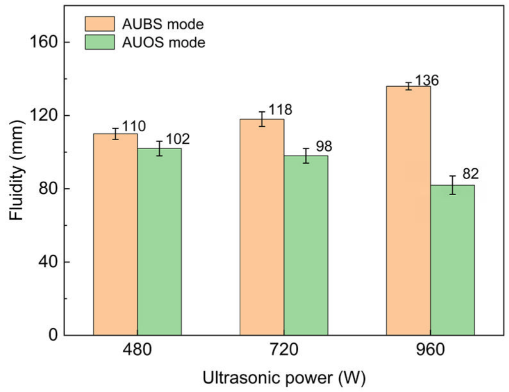
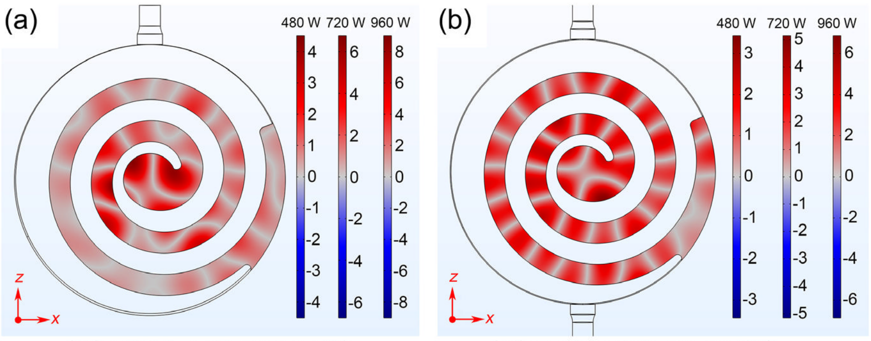


Fig. 9: Influence of ultrasonic power on fluidity of AlSi9Cu3 alloy under AUOS and AUBS modes

In order to verify the cavitation effect, the acoustic pressure distribution in the AlSi9Cu3 melt (density and sound velocity of liquid AlSi9Cu3 at 953 K are 2,350 kg·m^{-3} and 5,496 m·s^{-1}, respectively) was calculated, given the cavity was full of melt without any solidification. As shown in Fig. 10, the maximum acoustic pressure in the melt under the AUOS and AUBS modes reaches 3–8 MPa with different input power, and is higher than the reported cavitation threshold of 1 MPa in aluminum alloy [4]. Therefore, acoustic cavitation is considered to occur during the melt filling of the mould cavity. This can be verified by the less branched and short rod-like primary α-(Al) dendrites, as well as the finer eutectic Si in alloys solidified under both the AUOS and AUBS mode, as shown in Fig. 11, which are possibly induced by the cavitation effects. In addition, the secondary dendrite arm spacing is 13.8±0.5 μm when no ultrasonic vibration is applied, 10.8±0.3 μm in AUOS mode, and 10.5±0.2 μm in AUBS mode. It can be found that the ultrasonic effects such as cavitation and acoustic streaming caused by the ultrasonic vibration of the mould have the effect of reducing the secondary dendrite spacing and refining the structure.

According to the melt flow stop mechanism, the fluidity of the alloy melt is closely related to the crystallization temperature range and crystallization mode of the melt in the casting process [19-21]. When the melt cools below the liquidus, the dendrites begin to nucleate and grow. As the temperature further decreases, the dendrites develop to form skeletons and block the flow channel. The melt flow stops when the flow pressure cannot overcome the resistance of dendrites skeletons, as schematically shown in Fig. 12(a). When an ultrasonic vibration is applied to the melt during solidification, the



Surface: Total acoustic pressure, RMS

Surface: Total acoustic pressure, RMS

Fig. 10: Simulated acoustic pressure in the melt under AUOS mode (a) and AUBS mode (b)

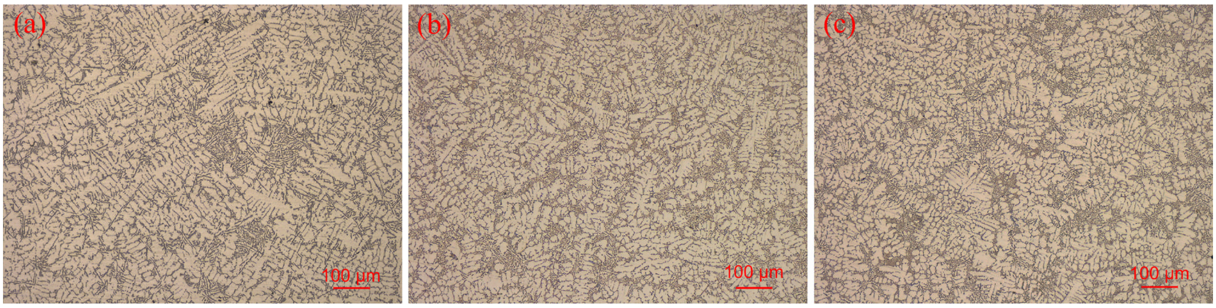


Fig. 11: Microstructures of AlSi9Cu3 alloy: (a) no ultrasonic vibration; (b) under AUOS mode (ultrasonic power 960 W); (c) under AUBS mode (ultrasonic power 960 W)

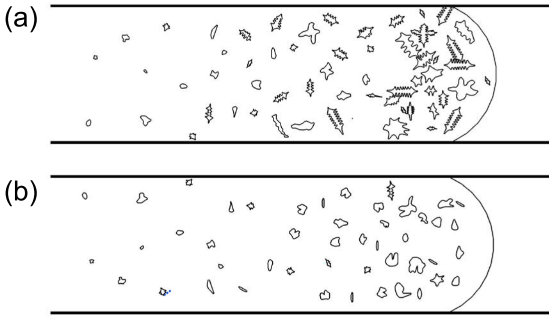


Fig. 12: Schematic diagram of influence mechanism of ultrasonic vibration on fluidity of alloys: (a) no ultrasonic vibration; (b) apply ultrasonic vibration to the lower mould

ultrasonic cavitation and acoustic flow effects can break the dendrites, thereby reducing the flow resistance and improving the fluidity of the melt, as schematically shown in Fig. 12(b).

However, the non-uniform displacement of the mould surface will produce non-uniform acoustic pressure distribution in the melt, inducing melt flow from the high acoustic pressure area to the low acoustic pressure area, as shown in Fig. 13. The melt flows collide in the low acoustic pressure area and form a turbulent area, which intensifies the melt turbulence and consequently decreases the fluidity. This is similar to the abovementioned result regarding the distributions of ceramic sands driven by ultrasonic vibration in the mould cavity.

In addition, the acoustic streaming opposite to the melt filling direction also can dissipate the energy of the melt flow and decrease the fluidity. The above decreasing effects are proportional to the non-uniform displacement gradient. The study on seed oil showed that the 20 kHz ultrasonic vibration with amplitude 30 μm can induce a maximum acoustic streaming velocity of 0.4 m·s^{-1} [22]. This streaming velocity is of the same order of magnitude with the flow velocity of aluminum melt 0.4 m·s^{-1} (calculated by ProCast software) during the mould filling process in the present work. Therefore, it is reasonable to consider that: the vibration gradient under AUOS mode is more non-uniform and high enough to induce a violent melt flow toward the weak vibration areas and turbulence there, consequently decreasing the casting fluidity; however, the gradient under AUBS mode is relatively uniform and low, and the generated melt flow and turbulence is too weak to offset the abovementioned promoting effects (dendrite broken, prompted wetting and so on) on fluidity.

In summary, the fluidity of the melt under ultrasonic vibration is subject to the above two aspects: the dendrite broken effect improving fluidity; and the uneven displacement

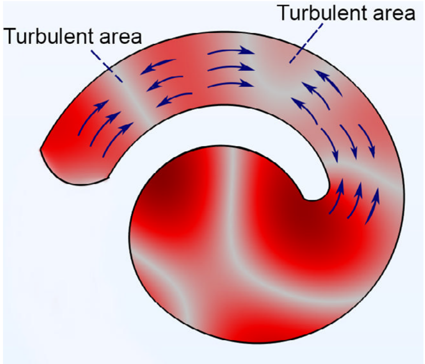


Fig. 13: Schematic diagram of melt turbulence induced by non-uniform displacement gradient under AUOS vibration mode

gradient (vibration gradient of mould) decreasing fluidity. The final effect of ultrasonic vibration on fluidity depends on which of these two aspects plays a dominant role. Such as, if the uneven displacement gradient is high enough, the fluidity of the melt is finally decreased although dendrites are also broken during solidification, as in the AUOS vibration mode in the present work. It should be stressed that the calculated acoustic pressure distribution is only used as reference to interpret the influence of vibration gradient on fluidity, because the calculation did not take into account the accompanied solidification during filling, as well as the time dependence characteristic. Also, acoustic streaming would be more complex if cavitation and interface waves induced by vibration are involved. Therefore, a more delicate study should be carried out in future on the fluid mechanics aspects.

4 Conclusion

The influence of non-uniform ultrasonic vibration on the fluidity of liquid AlSi9Cu3 alloy was studied through mould vibration with two different modes. The two different modes were generated respectively by applying ultrasonic vibration on only one side of the mould (AUOS) and both sides of the mould (AUBS). The mould vibration under the AUOS mode has higher vibration gradient and is more non-uniform than that under the AUBS mode. Fluidity experiments indicate that the relatively uniform mould vibration with small vibration gradient under the AUBS mode can promote casting fluidity, however, the non-uniform mould vibration with large vibration gradient under the AUOS mode does the opposite. It is found that the ultrasonic mould vibration can generate two opposite effects on the casting fluidity: first, ultrasonic cavitation in melt induced by mould vibration promotes the casting fluidity; second, the non-uniform mould vibration can induce a melt flow toward the weak vibration areas and turbulence there, consequently decreasing the casting fluidity. When the melt flow and turbulence are violent enough to offset the promoting effect of cavitation on fluidity, the ultrasonic vibration will finally induce a resultant decrease of the casting fluidity. The decreasing effect is proportional to the vibration gradient.

Acknowledgements

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