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# Microstructural characteristics and mechanical properties of peritectic Cu–Sn alloy solidified within ultrasonic field

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The dynamic solidification of peritectic Cu–70%Sn alloy was accomplished within a 20 kHz ultrasonic field under the power range up to 440 W. The ultrasound promotes the nucleation of primary $\varepsilon$(Cu$_3$Sn) phase and prevents the bulk undercooling of liquid alloy. As sound power increases, the ultrasonic field brings about a striking size refinement effect to the primary $\varepsilon$ intermetallic compound by more than one order of magnitude. Meanwhile, it facilitates or even completes the usual peritectic transformation $(L + \varepsilon \rightarrow \eta)$ which occurs only to a very limited extent during static solidification. This is mainly because the refinement of primary $\varepsilon$ phase induced by ultrasound greatly reduces the characteristic length of peritectic microstructure, which increases solid state Fourier number by more than one order of magnitude. The dramatic increase in the volume fraction of peritectic phase and the prominent grain refinement effect due to ultrasound lead to the remarkable improvement of mechanical properties for Cu–70%Sn alloy, whose compressive strength and microhardness are increased by factors of 4.8 and 1.45, respectively.

## 1. Introduction

In recent years, peritectic solidification arouses great scientific interest since it plays an important role in the production of many commercial materials such as Ti–Al alloys [1]. During peritectic growth, a primary $\alpha$ solid phase always precipitates initially from parent liquid phase, followed by the nucleation and growth of a peritectic $\beta$ phase around it [2]. Since peritectic transformation is an atomic diffusion-controlled process which is very difficult to be completed, the final microstructures are almost always composed of some peritectic phase plus considerable amount of residual primary phase [3].

Extensive investigations have been done on peritectic solidification, particularly on the peritectic growth mechanism, including the coupled growth of primary and peritectic phases [4–7], the formation of banded peritectic structure [8], solute segregation [9], and the peritectic reaction rate and the growth velocity of peritectic phase [10,11]. There are also some reports on the relationship between peritectic microstructures and physical properties, which indicate that the refinement of primary solid phase usually leads to the promotion of peritectic reaction and thus enhances the mechanical performance of peritectic alloys [2,12]. Meanwhile, the volume ratio of peritectic phase to primary phase is also crucial for the physical properties of some peritectic systems [13]. For example, the magnetic performance of Nd–Fe–B alloy can be remarkably improved if the amount of peritectic phase increases [13]. Therefore, it is highly desirable to facilitate and even complete the peritectic transformation during liquid to solid transition for the sake of both scientific research and industrial production.

In general, there are two feasible approaches to modify peritectic microstructures. By rapid solidification method, it has been recently demonstrated that the primary phase can be refined with the increase of undercooling. Moreover, if undercooling is sufficiently high, peritectic phase preferentially nucleates from metastable liquid alloy by preventing the nucleation of primary phase and hence suppressing the peritectic transformation in alloy system [14]. Another idea is to apply external fields such as ultrasound to peritectic solidification process. The application of ultrasonic field during liquid to solid transition is proved to be an effective way to improve the solidification microstructures and mechanical properties [15,16]. The ultrasonic wave brings about such nonlinear effects as cavitation and acoustic streaming, which greatly affect the crystal nucleation and growth process. Most recent work reports on dendritically solidified Al based [17,18] and Mg based [19,20] alloys, and the common finding is that the previously coarse (Al) and (Mg) dendrites turn into refined

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equiaxed or globular grains in the presence of ultrasound. However, there are few literatures on the effect of ultrasound on peritectic solidification. It could be optimistically speculated that the introduction of ultrasound into peritectic growth can lead to combined effects of the refinement of primary phase and the promotion of peritectic transformation.

Cu–70%Sn alloy is a typical peritectic alloy, whose primary phase is an intermetallic compound $\varepsilon(Cu_3Sn)$ showing faceted growth, and the peritectic product is another intermetallic compound $\eta(Cu_6Sn_5)$ with a very narrow composition range. The peritectic transformation rate for this type of peritectic alloys is always very slow under normal conditions. In this work, an ultrasonic field of 20 kHz is introduced to the peritectic solidification process of Cu–70%Sn alloy. The effect of ultrasound on the dynamic nucleation characteristics of primary and peritectic phases is studied. The peritectic solidification mechanism within ultrasonic field is discussed on the basis of the peritectic microstructure evolution versus ultrasound power. Finally, the mechanical properties of Cu–70%Sn alloy after ultrasonic solidification are investigated.

## 2. Material and methods

The experiments were conducted in a unidirectional solidification apparatus incorporated with an ultrasonic generator at a resonant frequency of 20 kHz. The Cu–70%Sn alloy sample was $\Phi\ 8 \times 20$ mm in size and was contained in $\Phi\ 8 \times 40$ mm steel crucible, whose bottom was contacted closely with the ultrasonic horn. During experiments, the sample was heated and molten by an electrical resistance furnace under the protection of flowing argon atmosphere. When the liquid alloy dropped to a temperature of 100 K higher than its liquidus temperature, the ultrasonic transducer was turned on, and the ultrasonic wave was transmitted into the liquid alloy from its bottom until the alloy sample solidified completely. It needs to be mentioned that the principal heat flow was along the axis of the steel mold, and the solidification process initiated from the bottom of the alloy sample. The melt temperature was monitored by a NiCr–NiSi thermocouple positioned at the middle part of the sample and he cooling curve was recorded by a type 3067 recorder. Different voltages (0, 50, 100 and 200 V) were input to the ultrasonic transducer. The corresponding ultrasound power was estimated to be 0, 110, 220 and 440 W, respectively. After experiments, the solidified samples were vertically sectioned, mounted, polished and etched. The phase constitution, microstructure and solute distribution of solidified samples were analyzed by a Rigaku D/max 2500 X-ray diffractometer (XRD), a Zeiss Axiovert 200 MAT optical microscope (OM) and a Shimadzu 1720 electron probe microanalyser (EPMA).

An HMV Shimadzu Microhardness Tester was applied to measure the microhardness of the primary $\varepsilon$ phase. The loading force on each point was 490.3 mN with time duration of 15 s. In order to investigate the effect of ultrasound on constitutive relationship of Cu–70%Sn alloy, specimen in a size of $\Phi\ 3.0 \times 3.0$ mm were cut from the top and bottom parts of each alloy sample solidified under different ultrasound powers, and the static compression tests were performed by CSS44100 universal electronic testing machine. The loading speed of mechanical testing machine was set to be 0.3 mm/min downward. To ensure the accuracy of test results, the compression without samples was also conducted to make a baseline correction of machine-stiffness.

## 3. Results and discussions

### 3.1. Dynamic nucleation of primary and peritectic phases

Fig. 1(a) shows the location of Cu–70%Sn alloy in the Sn-rich part of the published Cu–Sn binary phase diagram [21]. Under equilibrium condition, when temperature decreases to 871 K, primary $\varepsilon$ phase preferentially precipitates from Cu–70%Sn liquid alloy. Once temperature reaches 688 K, peritectic transformation $L + \varepsilon \rightarrow \eta$ occurs. On continuously cooling, eutectic transition $L \rightarrow \eta + (Sn)$ takes place in the residual liquid alloy at 500 K. Fig. 1(b) plots the cooling curves of Cu–70%Sn alloy under static condition and within ultrasonic field with sound power of 440 W. The three evident stages correspond to the three transitions indicated in binary Cu–Sn phase diagram [21]. During static solidification, the nucleation of primary $\varepsilon$ phase initiates at 837 K

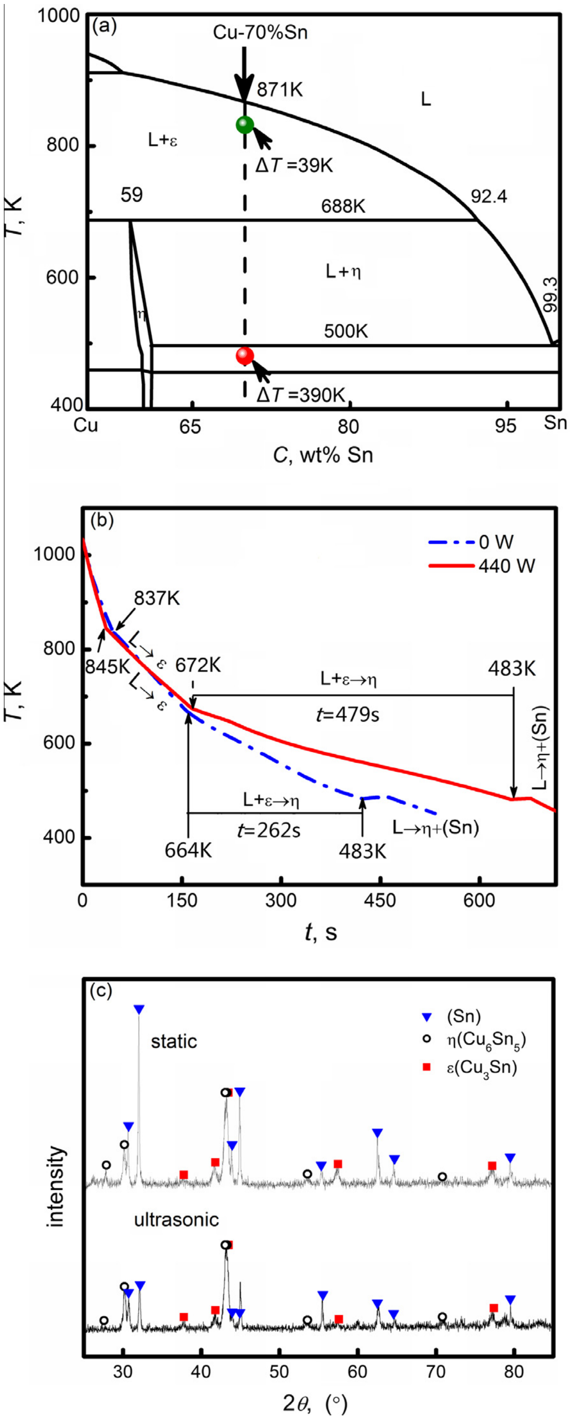

**Fig. 1.** Selection of alloy composition, cooling curves and phase constitution: (a) the location of Cu–70%Sn alloy in phase diagram [21]; (b) cooling curves during static solidification and under power ultrasound of 440 W; and (c) XRD patterns under static condition and within ultrasonic field.