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Effects of High Pressure on the Solidification Microstructure of Al-Si Alloy

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Abstract: The microstructure of the aluminum-silicon (Al-Si) alloy solidified under high pressure was compared with that solidified under normal pressure. High-pressure solidification was performed at 4.0 and 5.0 GPa. The microstructures of the samples were observed by optical microscopy, scanning electron microscopy, and transmission electron microscopy (TEM). The effects of pressure were analyzed by examining the microstructure of the alloy. The observed microstructures show an additional amount of primary α(Al) phase in the Al-13at%Si alloy solidified under high pressure; this indicates the existence of a eutectic point moving toward the silicon direction with increasing pressure. The eutectic cells of the Al-Si alloy solidified under high pressure are evident, and the eutectic silicon phases are presented as curved and near-parallel lamellar crystals, signifying that the growth mechanism of the eutectic silicon phase changed from faceted to non-faceted. The eutectic silicon lamellar phase and the primary β(Si) phase were refined by the applied pressure.

1 Introduction

Aluminum-silicon (Al-Si) alloys are suitable alternatives to ferrous alloy components because of their light weight and superior cooling and tribological properties. Both hypo- and hypereutectic Al-Si alloys have shown potential as engine block materials due to their adequate wear resistance and high strength-to-weight ratio[1~3]. High-pressure die casting is the most commonly used shape casting method for this material[4~6]. Pressure is an essential thermodynamic parameter that can influence the solidification process[7]. Solidification under high pressure can affect and control the nucleation and growth in alloys during solidification; this can alter the distribution of the second phase, uniformity of composition, and result in a non-equilibrium microstructure[8]. Controlling the microstructure is very important to obtain the suitable properties. In the present work, the microstructures of the Al-Si alloys of various compositions and solidified under different pressures were investigated.

2 Experimental

The Al-Si alloys (11, 13, 17, 21, 35, and 40 at.% Si) were prepared using aluminum (99.9% purity) and silicon (99.99% purity) in a water cooling copper crucible in a vacuum Ar-arc furnace. The smelting process was repeated 2–3 times to guarantee the uniformity of the alloys. Afterward, the 5×5×5 mm alloy samples packed with BN solvent were heated to 1500 °C for 8–10 min to melt the samples completely under different high pressures (4.0 and 5.0 GPa) on the hexahedral anvil equipment. The power was cut off, and the samples were cooled to room temperature at of ~10 $K \cdot s^{-1}$. Optical microscopy (OM), scanning electron microscopy (SEM) and transmission electron microscopy (TEM) were used to observe the microstructure of the Al-Si alloys, and X-ray diffraction(XRD) was performed to analyze the phase construction of the alloys.

3. Results and discussion

3.1 XRD spectrum of the Al-Si alloy solidified under high pressure

The XRD results of the alloy solidified under high pressure show that the phases are α(Al) and β(Si) solid solution and no new phase is observed (Fig. 1). Calculations indicate a slight decrease in its crystalline-lattice parameter compared with that of the alloy solidified under normal pressure. This is because the high pressure could decrease the spacing between atoms.

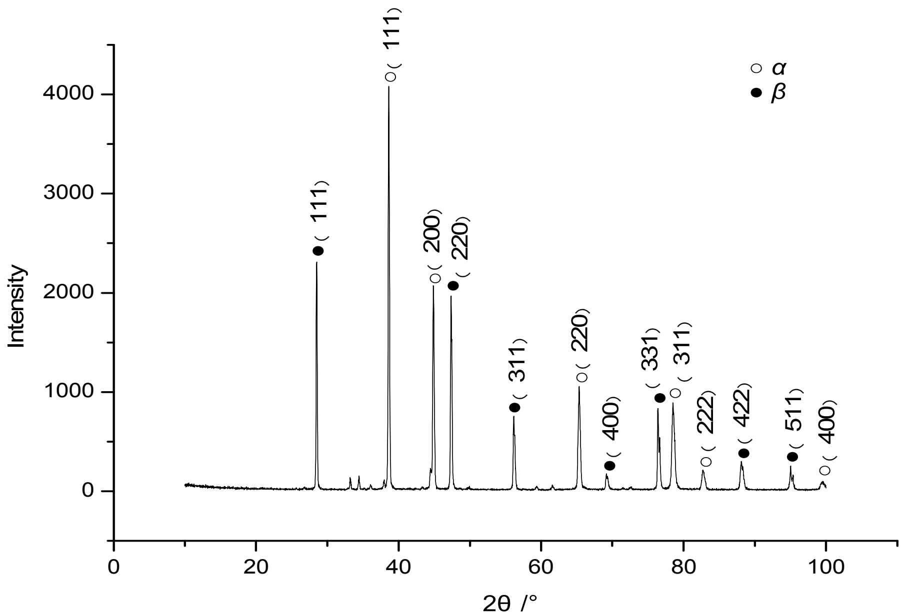

Fig. 1 XRD spectrum of hypereutectic Al-Si alloy solidified under high pressure

3.2 Effect of pressure on the primary α phase in the Al-Si alloy

Fig. 2(a) illustrates that the microstructure of the hypoeutectic Al-11at%Si alloy solidified under normal pressure was composed of a primary α phase and a dominant (α+β) eutectic phase. This is consistent with the solidification theory. However, at the eutectic point of the Al-13at.%Si alloy [Fig. 2(b)], a small quantity of the α phase remained in the eutectic phase. This is because of non-equilibrium solidification due to rapid cooling, leading the formation of the pseudo-eutectic region. The microstructure of the Al-13at%Si alloy solidified under 5 GPa [Fig. 2(c)] was composed of a primary α phase and an (α+β) eutectic phase. The quantity of the primary α phase of this alloy was more than that of the sample solidified under normal

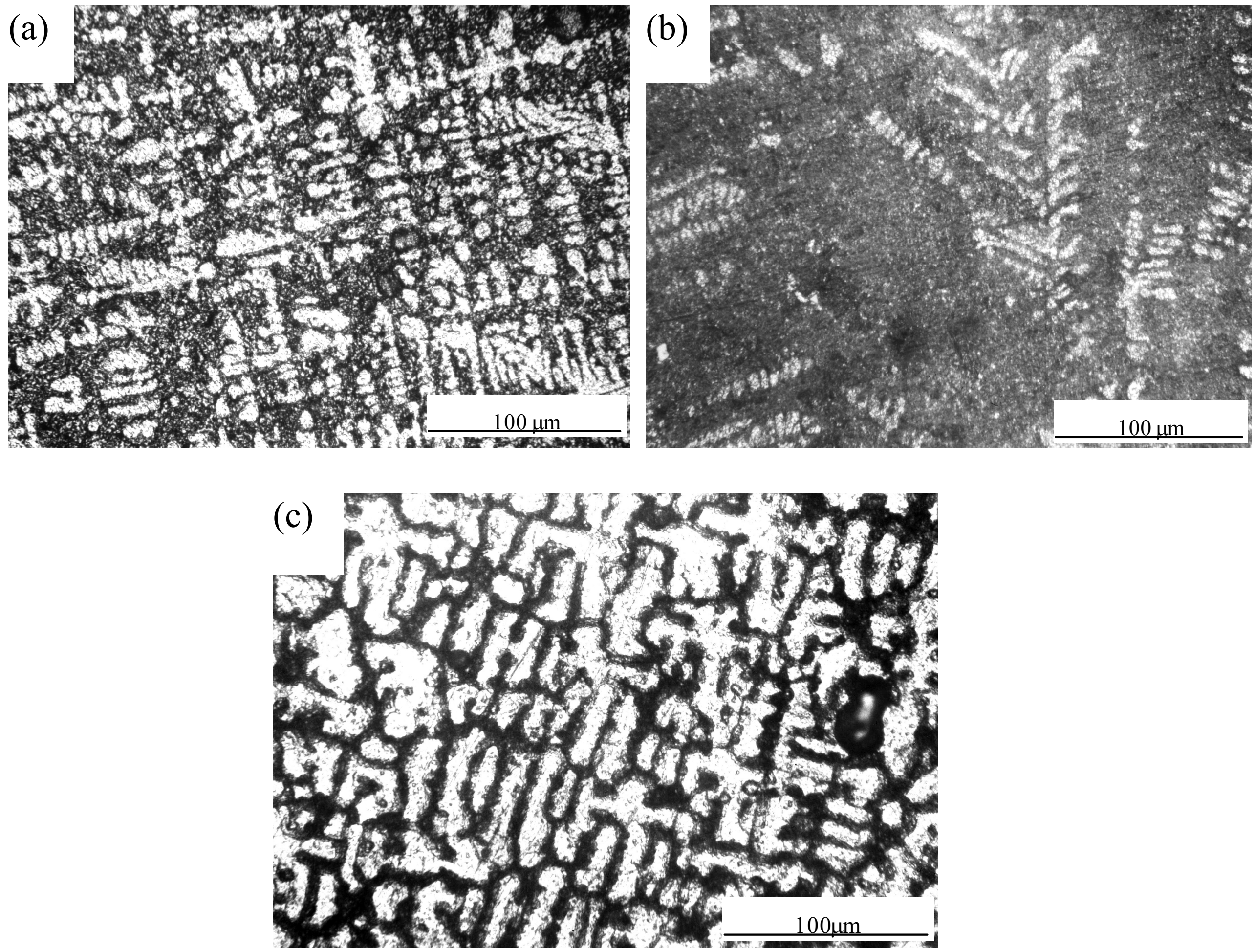

Fig. 2 Effect of pressure on the primary α phase in the Al-Si alloy. (a) OM micrograph of hypoeutectic Al-11at.%Si alloy solidified under normal pressure; (b) OM micrograph of eutectic Al-13at.%Si alloy solidified under normal pressure; (c) OM micrograph of hypereutectic Al-13at.%Si alloy solidified at 5 GPa

pressure. Additionally, the configuration of its dendrite was not evident; this indicates that the solid-liquid interface was relatively stable compared with that solidified under normal pressure. Considering the principles of thermodynamics, the eutectic composition of the Al-13at.%Si should form a completely eutectic structure. The presence of the α phase, however, is due to the influence of kinetic factors. The Al-Si alloy is a typical metal-nonmetal alloy, which have different growth mechanisms between the metal and nonmetal. The solid-liquid interface for aluminum is atomically rough. In such an interface, the atom can easily occupy any position; this leads to the growth of Al in the improper direction. In contrast, the solid-liquid interface for Si is atomically flat, leading to growth of Si toward the proper direction. Thus, the Al-Si alloy is a typical anomalous eutectic alloy. Due to the different growth mechanisms between Al and Si, the kinetic pseudo-eutectic region turned to the phase with slower growth as the undercooling was increased. In the Al-Si phase diagram, the α phase grew faster than the β phase did as the undercooling was increased. This is because the interface in the α phase was atomically rough, whereas the interface in the β phase was atomically flat. Thus, the pseudo-eutectic region turned to the Si phase; this caused the eutectic mixture to form the hypoeutectic alloy and the primary α phase.

When the alloy was solidified under high pressure, the pressure stabilized the solid-liquid interface in the primary α phase, and thereby decreased the diffusivity of the solute atoms. Additionally, the process increased the solid solubility of Si in the Al phase, which restrained the solute atom accumulating in front of the interface, and led to the growth of the primary α phase with the cellular fashion. This explains the higher quantity of the α phase and the indistinct configuration of the dendrite compared with those of the alloy solidified under normal pressure.

3.3 Effect of pressure on the primary β phase in the Al-Si alloy

The microstructure of the Al-21at.%Si alloy solidified under normal pressure was composed of the β, α, and (α+β) eutectic phases [Fig. 3(a)]. The α phase precipitated around the coarse sheet-like primary β phase, which is the abnormal eutectic structure,

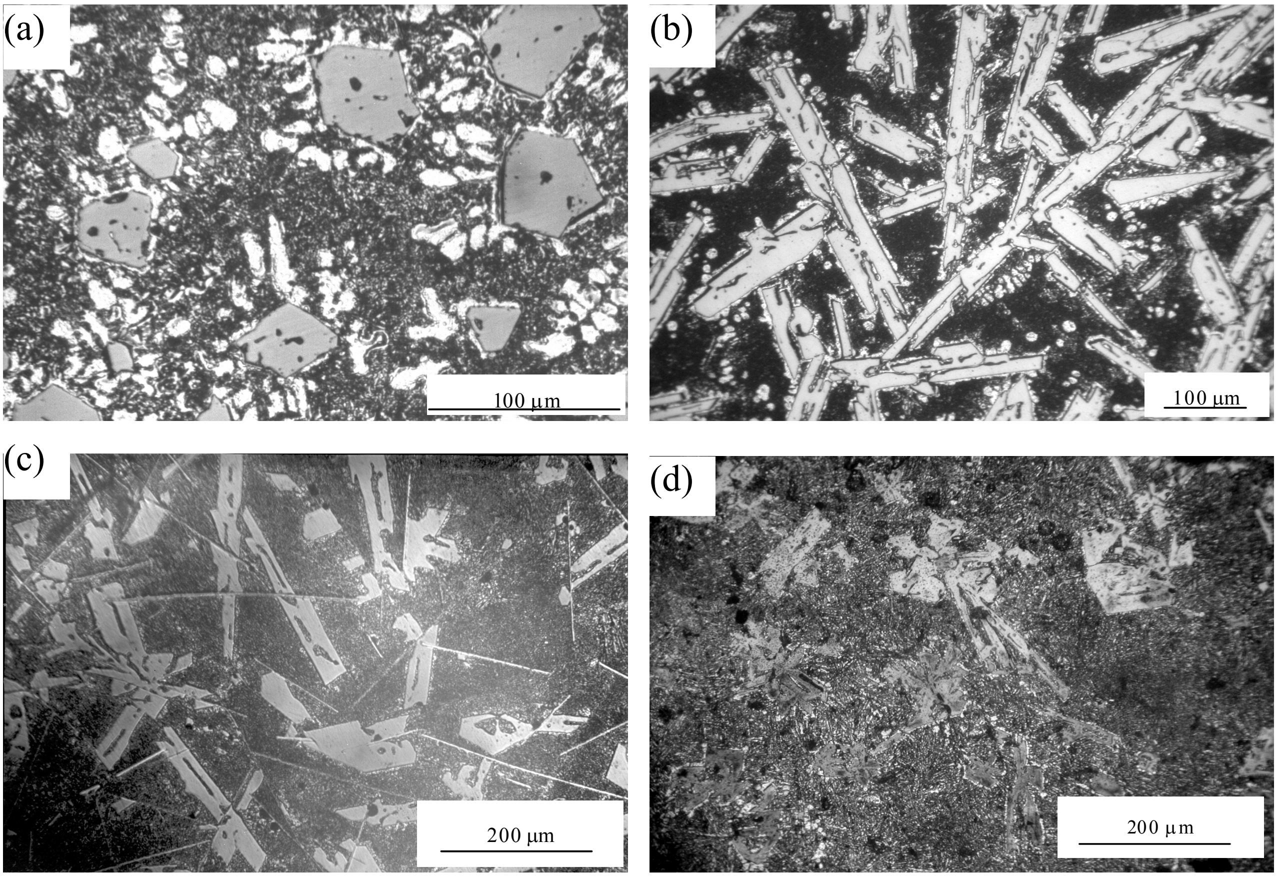

Fig.3 Effect of pressure on primary β phase in Al-Si alloy. (a) OM micrograph of hypereutectic Al-21at.%Si alloy solidified under normal pressure. (b) OM micrograph of hypereutectic Al-40at.%Si alloy solidified under normal pressure. (c) OM micrograph of Al-40at.%Si alloy solidified at 4 GPa. (d) OM micrograph of Al-40at.%Si alloy solidified at 5 GPa

because of the rapid cooling velocity (~100 $K \bullet s^{-1}$) when the alloy was smelted under normal pressure. During solidification, the β phase was initially precipitated; thus, the Al atoms could not diffuse completely due to the rapid cooling velocity accumulated around the β phase. This led to the composition of Al around the β phase fluctuating and precipitating α phase when the composition α phase reached the crystalline condition. As the cooling continued, the composition reached the eutectic point and fulfilled the eutectic transformation.

Fig. 3 (b) shows the microstructure of hypereutectic Al-40at.%Si alloy solidified under the crystal condition that was the same as that of Fig. 3 (a), which is different from that of Fig. 3(a) obviously due to the increasing Si composition. Increasing Si content decreases the composition fluctuation, leading to a different morphology of the primary Si phase.

Figs. 3(c) and (d) show the microstructures of the Al-40at.%Si alloy solidified under 4 and 5 GPa, respectively. The figures indicate that the primary β phase was significantly lessened and became finer compared with that of the alloy solidified under normal pressure. Pressure can decrease the activation energy of nucleation which, in turn, increases the nucleation rate. However, pressure can decrease the diffusivity and thereby decrease the velocity of crystal growth. These two conditions led to the refinement of the microstructure solidified under high pressure. Thus, the microstructure of the primary β phase of Al-40at.%Si alloy solidified under high pressure presented a finely clump structure rather than the coarse lath-shaped structure of alloys solidified under normal pressure.

3.4 Effect of pressure on the morphology of eutectic structure in the Al-Si alloy

Fig. 4(a) shows the SEM micrograph of the eutectic structure of Al-13at%Si alloy solidified under normal pressure; the sample was processed by heavy etching to remove the Al phase and retain only the Si phase in the eutectic region. The microstructure is a complicated net-like structure composed of acicular eutectic Si phase branches with no definite spacing between the layers.

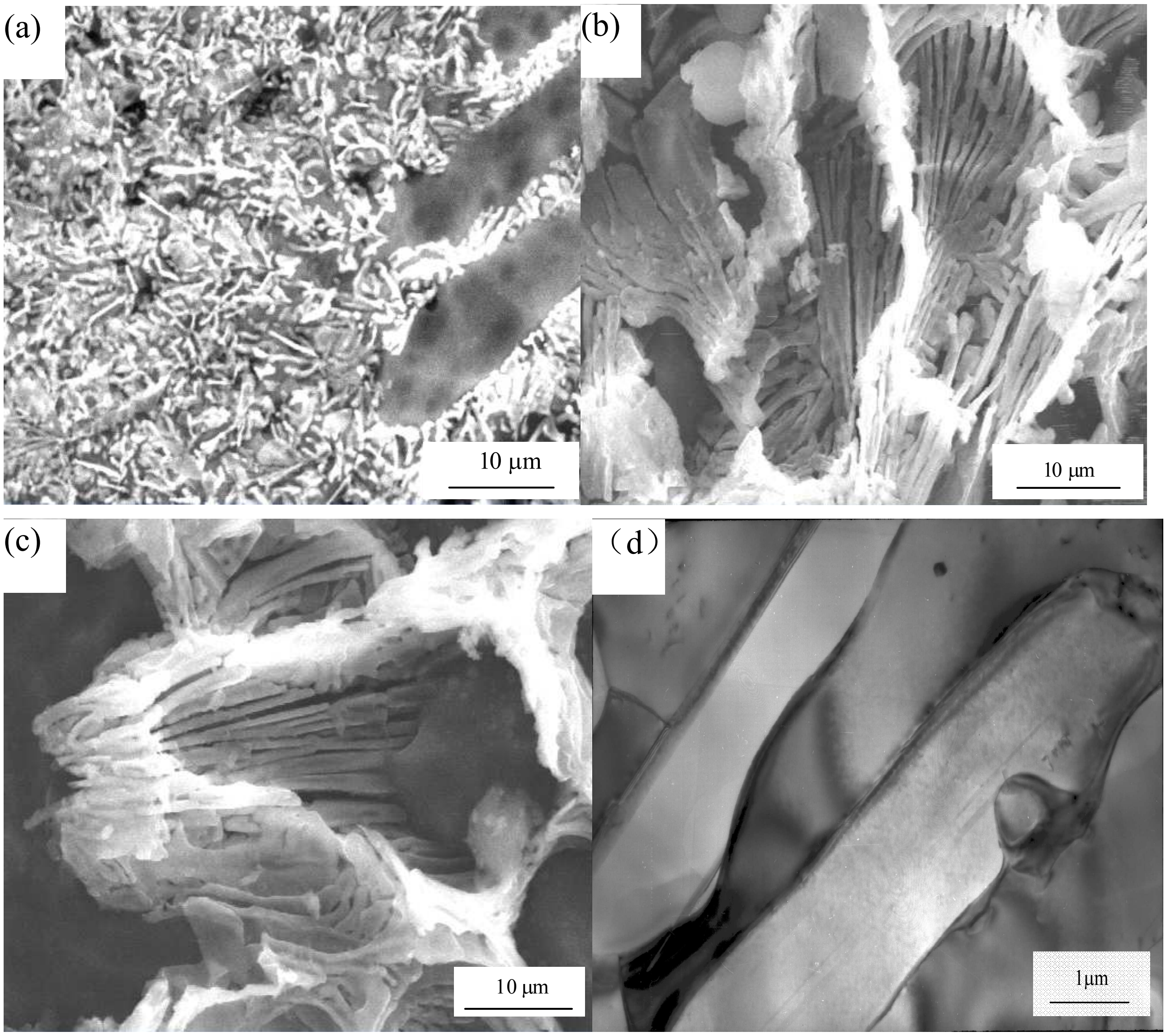

Fig.4 Effect of pressure on morphology of eutectic structure in Al-Si alloy. (a) SEM micrograph of Al-13at.%Si alloy solidified under normal pressure. (b) SEM micrograph of Al-13at.%Si alloy solidified at 5 GPa. (c) SEM micrograph of Al-17at.%Si alloy solidified at 5 GPa. (d) TEM micrograph of eutectic silicon at Al-35at.%Si alloy solidified under high pressure

During eutectic growth, the Al and Si phases interacted with each other and led to the constantly changing growth direction of Si. Thus, the solidified structure was intercrossed, and the eutectic cell was hardly evident. If the Si crystals did not connect with each other, the Si crystal should not have been reserved due to the absence of support because Al was etched off. The observed connection of the preserved crystals Si with each other to form the net-like structure indicates that the growth of the Si phase should not lag behind the Al phase during the eutectic solidification of the Al-Si alloy under normal pressure.

Figs. 4(b) and (c) show the SEM micrograph of Al-13at.%Si and Al-17at.%Si alloys solidified under 5 GPa. The primary α and eutectic α phases were removed due to the heavy etching; this formed a concave pit, in which the morphology of a eutectic lamella could be found which is very different from that of the alloy solidified under normal pressure.

Fig. 4(c) clearly shows the eutectic cell. When eutectic crystallization occurred under high pressure, the leading phase acted as the nucleation center for the growth of the eutectic Si phase. Crystal growth followed a parallel lamellar pattern around this center until they touched each other and formed the rosette eutectic cell structure.

Fig. 4(d) shows the TEM morphology of the hypereutectic Al-35at.%Si alloy solidified under high pressure. The edges and corners of Si became curved and smooth when it crystallized under high pressure. This suggests that the growth mode of Si have been gradually altered from faceted to non-faceted under high pressure.

4. Summary

Experiments on the eutectic and hypereutectic Al-Si alloys solidified under different pressures have been performed. No new phase was observed when the Al-Si alloy solidified under high pressures up to 5 GPa. With increasing pressure, the eutectic microstructure was obviously refined, and the eutectic point moved gradually toward the Si direction. Sketch maps of the Al-Si alloy under different pressure were drawn.

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