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Semi-solid characteristics and thixoforming of hypereutectic Al-Si alloy[①]

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Abstract: Effects of processing parameters on microstructure evolutions by mechanical stirring, procedures for obtaining thixotropy in semi-solid slurries, and procedure for thixoforging component, were investigated in hypereutectic Al-Si alloy. It is shown that 605 ℃ was the proper temperature for stirring treatment of this alloy, at which the coarse and plate primary Si crystals were effectively changed to globular crystals with a mean diameter of 200 μm after 50 min stirring, that billets with excellent thixotropy were obtained after 50 min remelting at 575 ℃, in which solid fraction of matrix and primary Si crystals was about 60 %, and that a perfect near net shape component of disc casting was obtained by thixoforging.

Key words: hypereutectic Al-Si alloy; primary Si crystals; thixoforming **Document code:** A

1 INTRODUCTION

Hypereutectic Al-Si alloy is a desirable material for manufacturing wear resistant components such as pistons in engine with low expansion coefficient and excellent wear resistance. However its substantial applications in industry are restrained by two issues: 1) its mechanical properties, tensile and fatigue strengths are drastically deteriorated because of the existence of a great stress concentration field during working in a cycle stress in the front of a tip of a plate-like primary Si crystal in the matrix; and 2) its machinability is extremely poor because of the very high hardness of primary Si[1]. Therefore it is necessary to change plate-like appearance of primary Si to globular-like one and to exploit a new forming process for near net shaping hypereutectic Al-Si alloy component which needs no or very little machining.

In recent years, researches on the semi-solid forming for near net shaping components in the worldwide focused on hypereutectic aluminum alloys, magnesium alloys, zinc alloys, tool steel and stellite. In these researches characteristics of evolution processing of the primary α grains in semi-solid temperatures and process routes for semi-solid forming through die-casting and forging were systematically investigated[2~11], however, research reported on semi-solid behaviors of hypereutectic Al-Si alloys is scarce so far[12,13]. In this investigation, semi-solid slurries of hypereutectic Al-Si alloy were obtained through mechanical stirring and a disc near net shaping component was formed by thixoforging after reheating a billet of the slurry at a temperature between solidus and liquidus, especially, thorough explorations of appearance evolution of the primary Si and thixotropy characteristics of the semi-solid billets were carried out.

2 EXPERIMENTAL

2.1 Composition of alloy

Al-25%Si-0.3%Mg-0.12% Ti alloy is used for semi-solid slurry and reheated billet preparations, and for thixoforging to form a near net shaping component.

2.2 Processes for semi-solid slurries

The alloy melts were mechanically stirred 50 min at 605 ℃ in a self-made installation to obtain semi-solid slurries which were then cast into a d54 mm cylindrical mould made of graphite to obtain semi-solid ingot. Slurry samples were sucked with a quartz tube from the melt for observing the appearances of primary Si.

2.3 Process for semi-solid billets

A 15 mm high billet cut from ingot was fixed in an electrical resistant vertical furnace and reheated at a temperature between solidus and liquidus to detect the relationship between thixotropy characteristic and reheating temperature as well as reheating time. The controlling precision of the furnace temperature is ±1 ℃. Samples for microstructure evolution observations were made directly from billets by quenching in liquid after reheating.

2.4 Process for thixoforging

Billet cut from ingot was installed in a die fixed in another self-made installation for both reheating and forging. This installation is fitted with a 990 kN

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plunger and a 40 kW electrical resistant furnace, and the billet was forged into a disc component with dimensions of d80 mm × 5 mm after reheating and holding at an optimum temperature and time.

3 RESULTS AND ANALYSES

3.1 Effects of semi-solid parameters on appearances of primary Si

Al-25 %Si-0.3 % Mg-0.12 %Ti alloy was stirred at a constant temperature of 605 ℃. Stirred by a 11 mm diameter agitator at a stirring speed of 900 r/ min, a shear rate of 100 s^{-1} was formed in the melt in a crucible with an internal diameter of 80 mm.

Fig.1(a) gives the same plate-like appearance of primary Si and Fig.1(b) a lump appearance with an angular structure which has a mean diameter of 480 μm in the range of 400 μm to 600 μm. Fig.1(c) and Fig.1(d) present globular appearance of primary Si after 30 min and 50 min stirring, respectively, from which it is known that the appearances of primary Si are changed from angular to globular and the diameters are finer during increasing the stirring time. After 30 min stirring globular primary Si grains with diameters in the range of 250 μm ~ 400 μm were obtained with a trace of angular structure, which had a mean diameter of 300 μm. And totally globular primary Si grains with diameters in the range of 150 μm ~ 260 μm were gained, which had a mean diameter of 200 μm after 50 min stirring. Distributions of all primary Si in both figures are homogeneous.

Fig.2 shows the variation of primary Si mean diameter with stirring time, from which it can be seen that there is a relation of exponential function between mean diameter (d) and stirring time (t) and that the slope of the curve at 50 min is very small, which means that no obvious decrease of diameter occurs during increasing the stirring time up to 50 min, therefore a stirring for 50 min at 605 ℃ is proper for this alloy.

3.2 Thixotropical characteristics and structural evolution during semi-solid reheating

3.2.1 Effect of reheating temperature on fluidity of billets

Particular issue for this alloy to get thixotropical billets is its low solid fraction of primary Si. Because the eutectic reaction of the alloy is at 573 ℃ determined by differential thermal analysis, billets were reheated at 580, 578, 575 and 573 ℃, respectively, to check the moment at which billets could not maintain their original shape and flowed down because of gravity. It is shown that the billet reheated at 580 ℃ flowed down in a few minutes, the billets at 578 and 575 ℃ flowed down in 40 min and 90 min, respectively, and the billet at 573 ℃ did not flow down and maintained its original shape in the period of reheating for 150 min.

3.2.2 Effect of reheating temperature and time on semi-solid structure

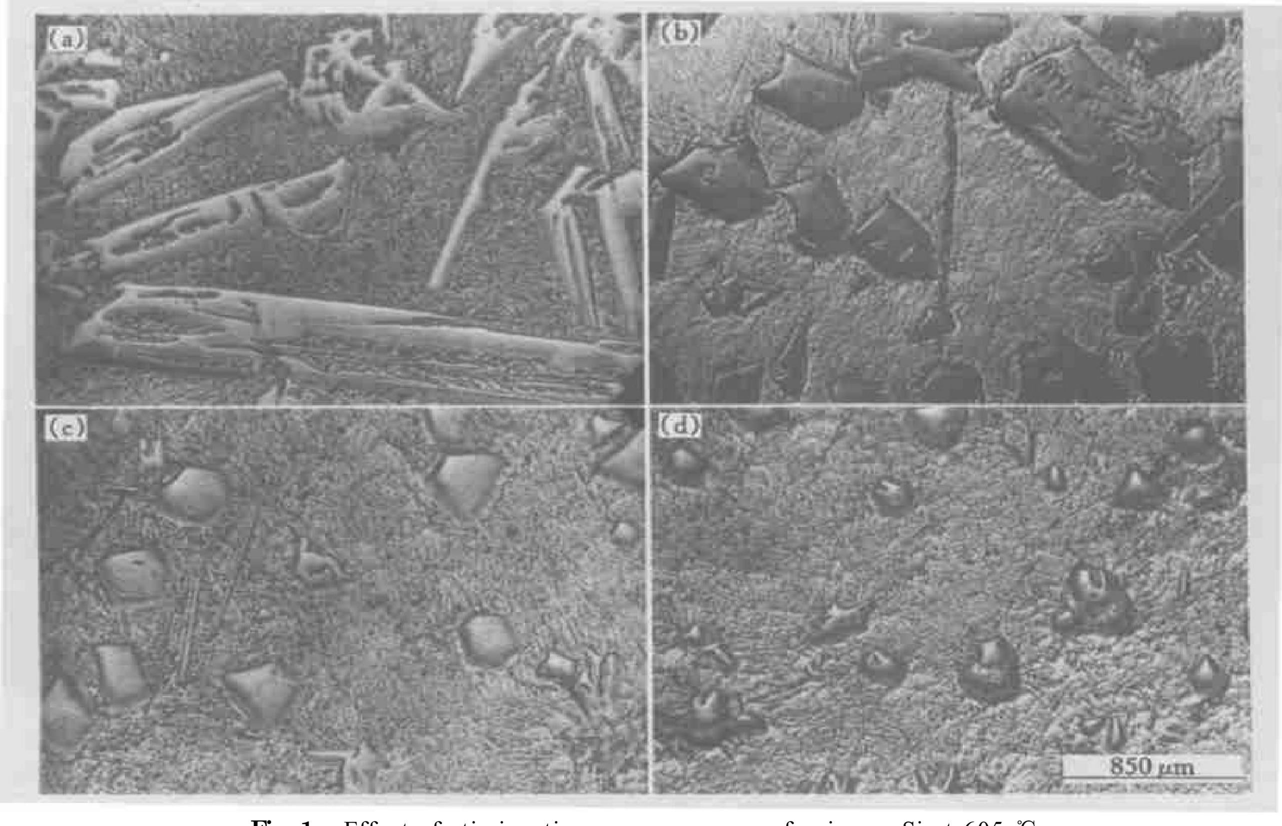

Fig.1 Effect of stirring time on appearance of primary Si at 605 ℃
(a) —0 min; (b) —20 min; (c) —30 min; (d) —50 min

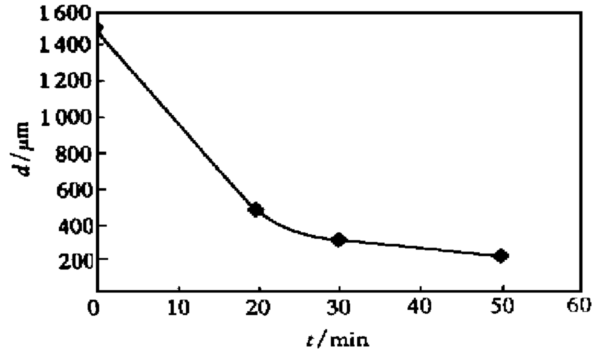

Fig.2 Relation between diameter (*d*) of primary Si grain with stirring time (*t*)

According to the experiment mentioned above, two reheating temperatures of 580 ℃ and 578 ℃ were given because of no thixotropy and the experiments were carried out at 575 ℃ and 573 ℃ to observe the appearance evolution with reheating time. It is observed from Fig.3 that, 1) the fusion speed of the matrix is extremely low; [There is a trace of fusion at some boundaries after 40 min(Fig.3(b)) and 90 min (Fig.3(c)) reheating and most of the matrix does not melt in the billet after 150 min reheating (Fig.3 (d)).] 2) despite minor change, the appearance of primary Si occurs from angular structure (Fig.3(a)) to globular one (Figs.3(b), (c) and (d)), more obvious globular appearance was observed with a sequence of reheating time; and 3) there is a tendency of refining of globular primary Si in reheating process with the sequence of reheating time.

Fig.4 shows the evolutions of primary Si and matrix structures reheated at 575 ℃. It is found that, 1) the fusion speed of the matrix is faster than that reheated at 573 ℃; [More than one third of the matrix was melted after 20 min reheating (Fig.4(a)) and about a half of the matrix was melted after 60 min reheating (Fig.4(b)), and all the matrix was melted after 120 min reheating (Fig.4(c)) and 150 min reheating (Fig.4(d)).] 2) there was a melt processing of primary Si during reheating; [Very fine primary Si grains shown in Fig.4(a) disappeared after 60 min reheating (Fig.4(b)). At the same time coarser primary Si grains were melted initially starting from angular points of grains, which made grain appearance change from angular to globular and their diameter being decreased.] and 3) colliding, amalgamating and coarsening of the primary Si grains occur after 150 min reheating (Fig.4(d)).

3.2.3 Thixotropy of semi-solid billet reheated

To investigate the thixotropy of the billet for semi-solid forging, cutting billet operations with a knife in semi-solid state were carried out at 573 ℃ and 575 ℃, respectively. While the billet reheated for 20 min at 575 ℃ could not be cut, the billet reheated for 50 min at the same temperature was smoothly cut into two pieces without any flowing and collapsing (Fig.5), which was an evidence for

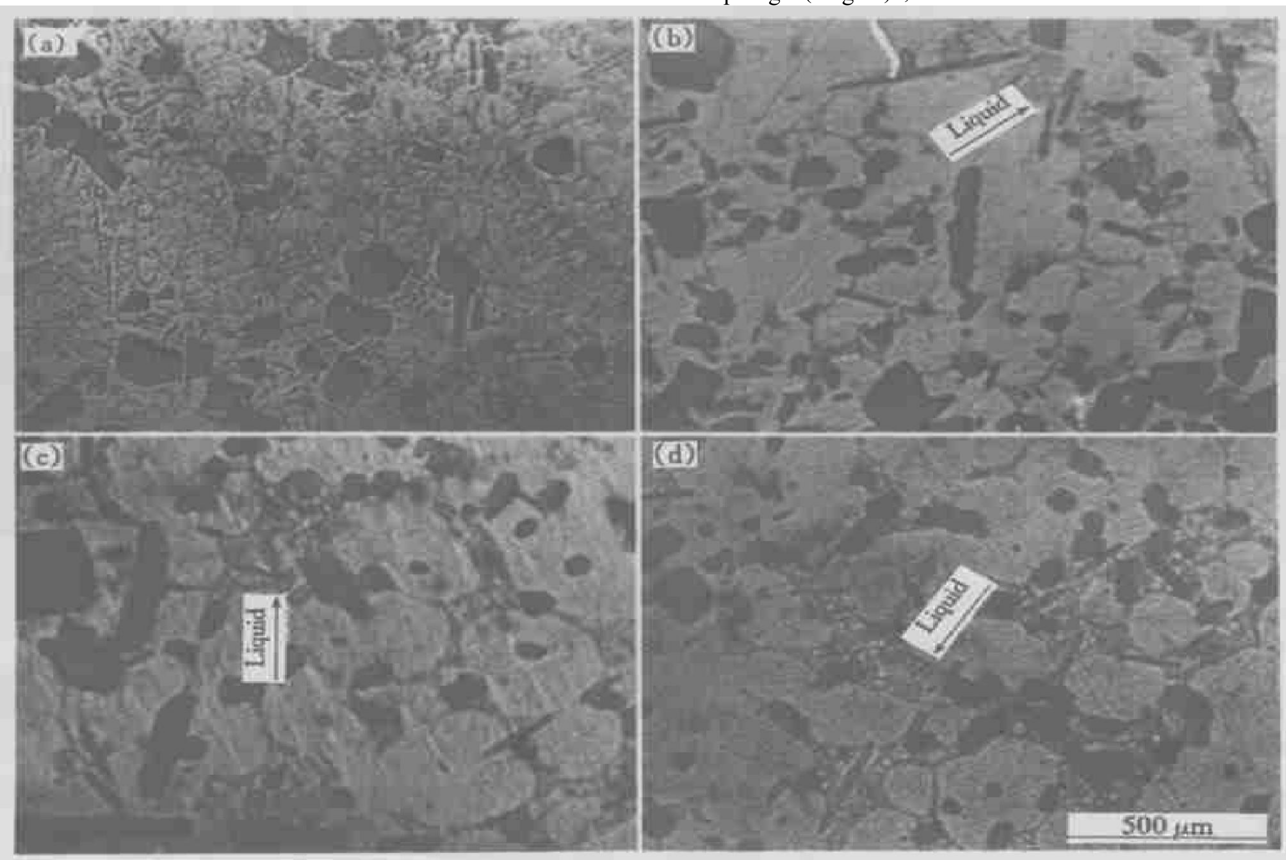

Fig.3 Variation of microstructure with reheating time at 573 ℃
(a) —0 min; (b) —40 min; (c) —90 min; (d) —120 min

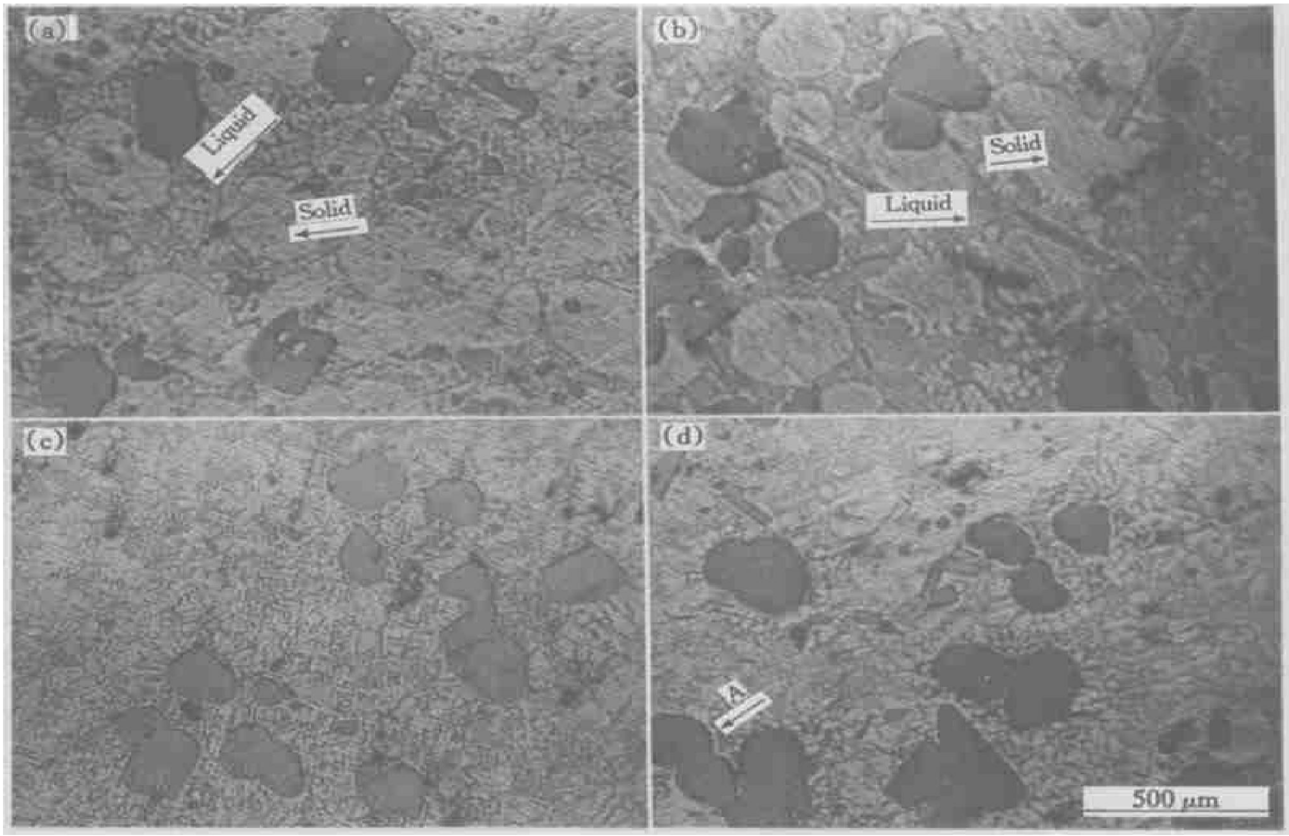

Fig.4 Variation of microstructure with reheating time at 575 ℃
(a) —0 min; (b) —40 min; (c) —90 min; (d) —120 min

superior thixotropical characteristic in this alloy. Contrarily, billets reheated at 573 ℃ could not be cut at any reheating time, even reheated up to 150 min, which means there is no thixotropy in the billet reheated at 573 ℃ any way.

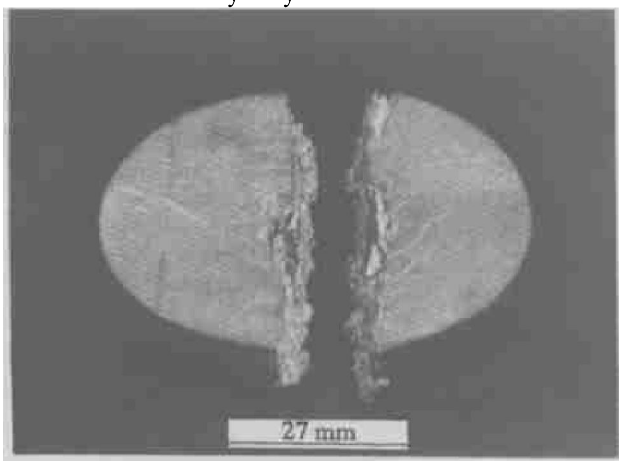

Fig.5 Appearance of billet cut after 50 min reheating at 575 ℃

3.3 Process for semi-solid forging and component formation

A billet cut from ingot was fixed in the installation made for semi-solid forging and reheated at 575 ℃. A disc component was fabricated by putting plunger down at a speed of 1.6 mm/s to forge the billet with a stress of 14 MPa after 50 min reheating. Fig.6 presents a good appearance of the component with perfect outline and smooth finish. The dimensions of disc component are d80 mm × 5 mm with another projecting cylinder of d40 mm × 5 mm.

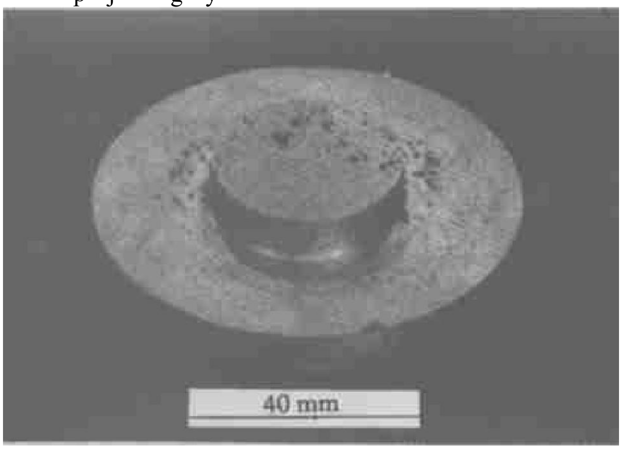

Fig.6 Appearance of disc component thixoforged

4 DISCUSSION

It is estimated from the binary Al-Si phase diagram that the solid fraction of primary Si is only about 13 % for these alloys during reheating at a temperature between solidus and liquidus, which gives no thixotropy in melt. It is vital to get a way to obtain thixotropy for semi-solid forging. It is verified in this investigation that the solid fractions of matrix of the alloy decrease with the sequence of increase of reheating time at 575 ℃. The solid fractions are 70 %, 50 % and 0 % with regard to reheating times of 20, 60 and 120 min, respectively. It is known from other researchers that perfect thixotropy is present when solid fraction of convention alloys is in the range of 30 % to 70 %. Therefore 50 min was chosen for reheating at 575 ℃, at which about 60 % of solid fraction existed in the alloy. Very perfect thixotropy was obtained by knife-cut operation and semi-solid forging operation. Conclusion is drawn from this analysis that perfect thixotropy of hypereutectic Al-Si alloys is realized not by controlling solid fraction of primary Si grains but by solid fraction of matrix. It is important to control the reheating temperature tightly close to solidus to form a period of time for fusion of matrix, which facilitates controlling solid fraction accurately.

5 CONCLUSIONS

1) Fine globular grains of primary Si with a mean diameter of 200 μm were gained through 50 min mechanical stirring at 605 ℃ in hypereutectic Al-25 % Si-0.3 % Mg-0.12 %Ti alloy.

2) For hypereutectic Al-Si alloy, thixotropy is realized not by controlling solid fraction of primary Si grains but by solid fraction of matrix. It is necessary to control both reheating temperature close to solidus and reheating time to get a proper solid fraction of matrix. In this investigation perfect thixotropy was gained with about 60 % solid fraction of matrix of the alloy by reheating billet 50 min at 575 ℃.

3) A disc component with dimensions of *d*80 mm × 5 mm was fabricated by thixoforging after 50 min reheating at 575 ℃. It is shown that semi-solid billets of the alloy processed under the parameters mentioned above had excellent capabilities of filling mould of die and gaining superior near net shaping components.

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