A New Process to Manufacture Semi-solid Alloys

Manabu KIUCHI and Sumio SUGIYAMA

Institute of Industrial Science, The University of Tokyo, Roppongi, Minato-ku, Tokyo, 106 Japan.

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A new process to manufacture semi-solid alloys was proposed. A testing machine was built and a series of experiments were carried out by using Pb–Sn alloys, aluminum alloys and cast irons with aim to characterize the process.

In each case, semi-solid alloys with varied levels of fraction solid, from low to high, were successfully manufactured by changing temperature of roll and shoe surfaces, gap between them, roll speed and superheating temperature of supplied molten metal. Through the tests, it has become clear that the proposed process is effective to manufacture various semi-solid alloys.

Mechanical properties of the alloys completely solidified after the semi-solid processing were investigated. The flow stress, hardness, elongation and deformability of the semi-solid processed alloys were measured. As the results, it becomes clear that their alloys have better quality than the conventionally cast alloys and, in some cases, their quality is distinctively improved by the semi-solid processing.

KEY WORDS: semi-solid metal; mushy metal; molten metal; mushy processing; semi-solid processing; solid fraction.

1. Introduction

In recent years, many attempts and investigations have been carried out with aims to develop new technology for manufacturing near-net shape products of alloys by controlling solidification of molten alloy as well as deformation of semi-solid (or mushy) alloy. (Hereinafter, the word “alloy” is used to express alloy as well as metal.)

These efforts are mainly focussed on two sorts of technologies. One is the technology to manufacture semi-solid (or mushy) alloys. Another is the technology to deform those semi-solid (or mushy) alloys into required near-net shape products.

As a technology to manufacture semi-solid alloys, “Rheocasting process” was proposed by M. Flemings.¹⁾ The outline of it is shown in Fig. 1(a). In this process, a molten alloy is poured into a crucible through an inletting nozzle. The poured molten alloy is mechanically agitated by a stirrer inserted to the crucible, and at the same time, cooled rapidly by a cooling device attached to the side wall of the crucible. Due to cooling, dendritic crystals grow on the inner surface of the crucible, however, they are crushed into small solid particles by the stirrer and dispersed in the remaining molten alloy. Thus a mixture of solid particles and molten alloy is manufactured and it is exhausted through an exit nozzle attached to the bottom of the crucible.

“Rheocasting process” was investigated by many research groups all over the world. Effects of dimensions of stirrer and crucible, revolutionary speed of stirrer, superheating temperature of molten alloy and cooling rate were widely investigated and discussed relating to apparent viscosity of semi-solid alloy being stirred in the crucible, obtainable fraction solid of exhausted semi-solid

alloy, shape and size of primary solid particles dispersing in it, internal structure and mechanical properties of product made of the semi-solid alloy.

Through those investigations, the following facts were made clear. (1) “Rheocasting process” is capable of manufacturing semi-solid alloys effectively. (2) However, when the fraction solid of the semi-solid alloy in the crucible becomes higher than roughly 40%, homogeneous mixing of primary solid particles with remaining molten alloy becomes difficult. (3) In such cases, it becomes difficult to exhaust the semi-solid alloy through the exit nozzle. (4) Under the appropriate stirring and cooling conditions, fine primary solid particles are obtained. (5) The minimum primary solid particle size obtainable by this process is roughly 30 to 50 micron meters.

From the results, the followings were also found. (1)

(a) Rheocasting Process

(b) SCR-Process

Fig. 1. Schematic illustrations of “Rheocasting process” and “SCR-process”.

“Rheocasting process” has several technological disadvantages. It is incapable of manufacturing semi-solid alloys with relatively high fraction solid. (2) This is due to the fact that “Rheocasting machine” based on the idea shown in Fig. 1(a) has poor ability for giving extrusion pressure to the semi-solid alloy in the crucible. (3) Furthermore, it has a mechanical structure inconvenient for giving high cooling rate to the molten alloy in the crucible. The high cooling rate is essentially necessary to obtain fine solid particles.

In order to utilize this process for real mass-production of semi-solid alloys, much more investigations are needed concerning desirable mechanical structure of “Rheocasting machine”, its necessary strength and stiffness, necessary driving power and torque, suitable materials for tooling, tool life, effective cooling system, method to control fraction solid, control system for stable operation and so forth. From these technological view points, this process is not always effective for actual production, where various semi-solid alloys with different levels of fraction solid and high productivity are needed.

In this study, in order to innovate the technology for manufacturing semi-solid alloys, the authors propose a new process, named as SCR-process (Shearing/Cooling Roll process). The outline of SCR-process and its characteristics are explained in the following chapters.

2. Outline of SCR-process

Figure 1(b) shows a schematic illustration of SCR-process.²⁾ A SCR-machine consists of a rotational shearing/cooling roll, a cooling shoe fixed to a supporting block and a stripper fixed to the machine frame. The roll and the shoe are set up so that the designed gap distance is kept between them. If necessary, they are cooled or heated by the cooling or heating device installed on the machine. The roll has an appropriate surface profile and is driven with designated rotating speed. The supporting block is removable on the machine bed and the gap between roll and shoe is adjustable.

The molten alloy, which is heated up to the required temperature, is poured into the roll-shoe gap through a flow-guide attached to the entrance (top) portion of the gap. The molten alloy is drawn into the roll-shoe gap by frictional force given by the rotating roll. At the gap, it is cooled by the shoe as well as the roll and, at the same time, stirred up by shear force given by the roll.

Due to the cooling, solidification of the molten alloy starts and dendritic crystals grow on the roll's and shoe's surfaces. But they are crushed into small solid particles by the shear force given by the roll. Those particles disperse in the remaining molten alloy and, through stirring, the mixture of solid particles and molten alloy is made. Thus the molten alloy changes to the semi-solid alloy.

The semi-solid alloy is drawn downward by the roll. Finally it is extruded out of the roll-shoe gap, where the stripper is installed closely to the roll surface and strip off the semi-solid alloy adhering to the roll surface.

The SCR-process and SCR-machine have the follow-

ing advantages. (1) The mechanical working principle and the structure of SCR-machine are simple. Therefore, both of operation and maintenance are easy. This is a very important advantage for sizing up the machine and applying the process to real production. (2) The roll surface does not contact with the molten alloy continuously, but periodically. Due to this, the roll surface temperature does not rise up to so high. Therefore, the high temperature strength of the roll material is not so seriously required. This means that the selection of material for the roll and other tooling becomes easy. (3) The roll and shoe of SCR-machine can be cooled more easily than the crucible and stirrer for “Rheocasting process”. If necessary, the hollow-roll and hollow-shoe can be employed. By using such roll and shoe, high cooling rate for the molten alloy can be attained. This is very important for getting fine solid particles dispersing in the semi-solid alloy. (4) The temperatures of roll surface and shoe surface, the gap between them and the roll speed are independently adjustable, therefore, the appropriate working conditions for manufacturing required semi-solid alloys can be realized easily.

3. SCR-testing-machine and Experimental Conditions

A series of experiments have been carried out in order to characterize SCR-process and its products.^{2,3)} The materials for tooling and dimensions of the SCR-testing-machine are as follows. The roll is made of S45C and its diameter and barrel width are 400 and 100 mm. The shoe is made of two curved plates of SS41 of which thickness, width and length are 20, 100 and 250 mm, respectively. The plate's radius of curvature is 400 mm. Two curved plates are joined together and attached to the supporting block and used as the cooling shoe.

The gap between roll and shoe is changed by moving the supporting block installed on the machine bed. In the following tested cases, the roll-shoe gap is not exactly uniform along the roll's periphery. The top end gap, that is the entrance of the gap, is slightly wider than the bottom end gap. Therefore, the gap at the intermediate position is used as the representative value in following discussions.

The maximum speed of the roll is 112rpm and the maximum available driving torque is 100 kgf·m. The maximum allowable force for pushing the roll to the semi-solid alloy in the gap is 2 000 kgf.

The tested materials are Pb–19.2%Sn, several aluminum alloys and ferrous materials such as A2017, A5056, ADC12, FC30, FC20, FCD40, SUS304 and S45C. Their liquidus and solidus temperatures measured by the present authors are shown in Table 1.

Each alloy is melted by a high frequency induction furnace and superheated up to various levels of temperature. The superheat is in the range from 290 to 552°C for Pb alloy, from 596 to 859°C for Al alloys, from 1 225 to 1 325°C for cast irons, from 1 494 to 1 537°C for SUS304 and from 1 525 to 1 540°C for S45C. After the heating, the molten alloy is removed from the furnace to the SCR-machine and poured into the gap between

Table 1. Liquidus and solidus temperatures of tested alloys.

Alloy	Temperature (°C)	
	Liquidus	Solidus
Pb-19.2%Sn	272	178
A2017	641	513
A5056	638	568
ADC12	565	(Unclearified)
FC30		1183
FC20		1183
FCD40		1189
SUS304		1450
S45C		1459

Fig. 2. Schematic illustration of SCR-process in which a molten alloy changes into a semi-solid alloy.

S45C
 $T/T_L: 1.03$ $T_T/T_L: 0.44$

Fig. 3. Appearance of a semi-solid alloy in roll-shoe gap and its internal structure changing from coarse to fine grains.

rotating roll and stationary shoe through the flow-guide attached to the entrance of the gap. As occasion demands, the roll and the shoe are preheated so as to prevent excessive solidification of the molten alloy at the initial stage of processing.

4. Results and Discussion

The following symbols are used to express the working conditions.

$T(^{\circ}\text{C})$: temperature of molten alloy before pour-

ing.

$T_L(^{\circ}\text{C})$: liquidus temperature of alloy.

$T_T(^{\circ}\text{C})$: average temperature of roll and shoe surfaces before processing (before testing)

$L(\text{mm})$: gap distance between roll and shoe at intermediate position.

$R(\text{rpm})$: rotational speed of roll.

Figure 2 shows a schematic illustration of the change of a molten alloy to a semi-solid alloy at the roll-shoe gap. After coming into the gap, the molten alloy contacts with the roll and shoe surfaces and cooled rapidly. Then

Fig. 4. Some examples of extruded semi-solid alloys.

it starts to solidify and forms so-called shells temporarily on the roll and shoe surfaces. However, as the solidified alloy and the remaining molten alloy are drawn by the roll into the inner gap, the shells including dendritic structures are crushed into particles by the shear force given by the roll. These solid particles are dispersed and mixed with the remaining molten alloy through agitation given by the roll. Thus the molten alloy is made into the semi-solid alloy and drawn into the bottom of the gap. Then it is extruded out of the gap.

Figure 3 shows an appearance of an alloy remained and solidified at the roll-shoe gap after the roll stopped during operation. From the picture, the change of internal structure of the semi-solid alloy at the roll-shoe gap and the extrusion of it through the exit of gap are clearly observed.

Figure 4 shows some examples of appearance of extruded semi-solid alloy. Here, the appearance was observed after the semi-solid alloy finished solidification.

From the observed appearance of the extruded semi-solid alloy, the flow features of semi-solid alloys in SCR-process are roughly classified into three groups as follows.

(1) Case 1: In this case, the cooling is not sufficient and the solidification of the molten alloy does not proceed so much. Then, the fraction solid of the semi-solid alloy remains lower than roughly 30–40%. Due to this, it has very low viscosity and flows like the molten alloy itself. The semi-solid alloy flows out of the roll-shoe gap like water flows out of a faucet.

(2) Case 2: In this case, the cooling is effective and the solidification of the molten alloy proceeds to fairly high extent. The fraction solid of the semi-solid alloy becomes higher than roughly 40%. It has intermediate viscosity and flow like soft icecream. Even though the viscosity is relatively high, it is extruded easily from the roll-shoe gap by the frictional force given by the roll.

(3) Case 3: In this case, excessive solidification takes place at the roll-shoe gap. Roughly more than 80% of the molten alloy completes solidification and is crushed into particles or flakes by the roll. Due to this, the ex-

 Fig. 5. Effects of relative tool temperature (T_T/T_L) and relative molten alloy temperature (T/T_L) on appearance of semi-solid alloy.

cluded semi-solid metal looks like a lump of solid flakes and particles. Its appearance after complete solidification is very coarse and looks like a porous material.

From these results, the semi-solid alloys manufactured by SCR-process are classified as follows.

Case 1: fluidal semi-solid alloy

Case 2: slurry semi-solid alloy

Case 3: flaky semi-solid alloy

Figure 5 shows effects of the relative tool (roll and shoe) temperature (T_T/T_L) and the relative molten alloy temperature (T/T_L) on the appearance of the manufactured semi-solid alloy. The roll-shoe gap distance (L), the roll speed (R) and the tested alloys are shown in the figure. From this figure, the following results are obtained.

(1) When the temperature of the supplied molten alloy and that of the roll and shoe are higher than the upper critical value, the semi-solid alloy naturally becomes fluidal.

(2) On the contrary, when the both temperatures are

Fig. 6.
Effects of temperature of tool and molten alloy on size of solid particle in semi-solid alloy.

Fig. 7.
Effect of tool temperature on internal structure of semi-solid alloy.

Fig. 8.
Effect of roll-shoe gap distance on internal structure of semi-solid alloy.

lower than the lower critical value, the flaky semi-solid alloy is obtained.

(3) When the relative tool temperature (T_T/T_L) and the relative molten alloy temperature (T/T_L) remain in the range from 0.5 to 0.8 and from 0.95 to 1.20, respectively, and the combination of them is appropriate, the semi-solid alloy slurry is obtained.

(4) The relative (normalized) temperature range appropriate for making the semi-solid alloy slurry is almost identical for every alloy.

The fraction solid and the viscosity of the manufactured semi-solid alloy are affected by the cooling rate which is dominated by the tool (roll and shoe) temperature and the roll-shoe gap distance. Even though the tool temperature is unchanged, if the gap is made narrower, the cooling rate increases and semi-solid alloys more viscous than before are manufactured.

Figure 6 shows effects of the temperatures of tool and molten alloy on the size of solid particles included in the manufactured semi-solid alloy. When the relative molten alloy temperature (T/T_L) is not so high and the relative tool temperature (T_T/T_L) is relatively low, the size of solid particles becomes very small. In some cases, it remains in the range from 30 to 50 μm in diameter. When the superheat of the molten alloy is high, even though the solid particles made in the SCR-machine are fine, the internal structure of the solidified product becomes coarse. This is due to the fact that, in this case, the molten alloy does not solidify so much at the roll-shoe gap and the solidification mainly occurs without stirring and shearing after the semi-solid alloy comes out of the gap.

From these observed internal structures, it is known

that very fine grains can be obtained when high enough cooling rate is given to the molten alloy at the roll-shoe gap.

Figures 7 and 8 show effects of the tool temperature and the roll-shoe gap distance on the size of solid particle in the semi-solid alloy. When the tool temperature (T_T/T_L) is low and the roll-shoe gap distance (L) is small, the cooling rate becomes high, and consequently, the solid particle size becomes very small. It should be noticed that the effects of the gap distance are very serious.

Figure 9 shows the force-stroke curves measured with

Fig. 9. Force-stroke curves for hot extrusion of billets made by SCR-process and metal-die casting.

Fig. 10. Internal structures of billets subjected to hot extrusion test.

Fig. 11. Stress-strain curves of extruded bars.

Fig. 12.
Internal structures of extruded bars.

respect to hot extrusion of A-2017 billets. The billets were made of the semi-solid alloys obtained by SCR-process and metal-die casting. The bold lines show the force-stroke relationships for billets by SCR-process and broken lines show similar relationships for billets made by metal-die casting. From the results, it is known that the billets by SCR-process have flow stress lower than that of the billets by metal-die casting. This is caused by the fact that, as shown in Fig. 10, the billets by SCR-process have fine internal structures including no dendrites, on the other hand, the billets by metal-die casting include typical dendritic structures.

After hot extrusion, however, the products extruded from both groups of billets show similar mechanical properties. Figure 11 shows the stress-strain curves obtained by the tensile test of the extruded bars. The bold lines show the stress-strain curves of bars just after the hot extrusion. It can be known that the bars extruded from the billets by metal-die casting show higher stress

and lower elongation than those of bars made of the billets by SCR-process. The broken lines show the stress-strain curves of the bars after heat treatment. The mechanical properties of both groups of bars are improved by the heat treatment and they show almost same flow stress and elongation.

Figure 12 shows the internal structures of the extruded bars. Both groups of bars based on SCR-process and metal-die casting have similar internal structures. This is due to the fact that the internal structures of both groups of billets are changed to the so-called fiber structures by large amount of deformation given by the hot extrusion.

5. Conclusion

A new process, named SCR-process, was proposed and its characteristics were investigated with aim to establish an effective and productive technology for manufacturing semi-solid alloys. A testing machine was

built and a series of trials to manufacture semi-solid alloys were carried out by using lead alloy, aluminum alloys and ferrous materials. Through the tests, the following results were obtained.

- (1) Semi-solid alloys can be manufactured stably and effectively by SCR-process.
- (2) Semi-solid alloys with varied levels of fraction solid, from low to high, can be manufactured by SCR-process.
- (3) The size of solid particle can be reduced to 30–50 μm without difficulty by SCR-process.
- (4) Operation and maintenance of SCR-machine is easy due to the simple structure.
- (5) The billets or slugs obtained by SCR-process have

low flow stress and high deformability comparing with those obtained by casting.

- (6) From technological view points, it can be concluded that SCR-process is an advantageous process for mass production of semi-solid alloys.

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