Cooling Slope Casting Process of Semi-solid Aluminum Alloys: A Review

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***Abstract*— Cooling Slope casting process promises to be a simple yet useful technique to produce semi-solid feedstock for thixoforming processes. However, the challenge lies in the judicious choice of process parameters to obtain a desired microstructure in the semisolid feedstock. The present paper reviews various investigations made by researchers with different parameters of Cooling Slope casting process and highlights their importance which is divided into four sections. Initially, the fundamentals of semi-solid metal processing are discussed and the classification of semi-solid processing has been outlined. Secondly, focus was drawn on fundamentals of the Cooling Slope casting process, the mechanism involved, with a note on its advantages and drawbacks. The third section lays particular emphasis on Cooling Slope casting process parameters that affect the final microstructure of the feedstock. The final section deals with reheating and isothermal holding conditions to obtain a sound component and the mechanical properties obtained thereafter.**

Keywords*— Semi-solid metal processing; thixoforming; Cooling slope casting; Aluminum alloys

I. INTRODUCTION

Over the past four decades a substantial amount of work has been carried out in the field of Semi-Solid Metal Processing (SSMP) for its unique capability to form near-net-shape products. The key element in the SSMP is the globular microstructure rather than dendritic microstructure and it is the thixotropic behaviour of the semi-solid slurry which reduces the segregation and porosity in the castings [1-2]. Compared with conventional techniques, SSMP provides several advantages like higher product quality, lower forming temperature, higher production rate and improvement of the mechanical properties through microstructural refinement [3-6]. Thixoforming is one of the member of SSMP routes based on the thixotropic behaviour of alloys with non-dendritic microstructure in the semi-solid state. Moreover, thixoforming and related SSMP methods require thixotropic feedstock materials as starting material [4]. One of the many SSMP techniques is the Cooling slope (CS) casting process [7-9] which is simple, has minimal equipment requirements and which is able to produce feedstock materials for semisolid processing. When the feedstock is reheated to the semisolid temperature range, nondendritic, spheroidal solid particles in a liquid matrix suitable for thixoforming are obtained [10].

Aluminum alloys are amongst the most prominent materials used in the automotive industries. Among the Aluminum alloys, the Al-Si alloys have exceptional casting characteristics and most of the parts are made from conventional casting alloys such as A356 and A357, which provide high fluidity and good castability which makes them advantageous for both small and intricate castings such as motor parts and miscellaneous fittings as well as comparatively large structural shapes. Nowadays, many vehicles use Aluminum engine blocks instead of cast iron, so significant weight reduction is achieved. Aluminum castings are used in almost 100% of pistons, about 75% of engine cylinder heads, 85% of intake manifolds, and 40% of chassis applications in automotive power trains [11-15]. Every year millions of Aluminum alloy auto components are produced through thixoforming processing route. Therefore, the automotive industry highly needs thixoformed components which possess good elongation as well as enhanced mechanical properties [4].

Keeping in mind the current needs of the automobile industry, present state of the art of research work is focussed on semi-solid Aluminum alloys processed through CS casting route and this review paper is divided into four sections. The first section focuses on the brief description about the origin of SSMP, classification of SSMP, rheological behaviour of semi-solid slurries, mechanisms for formation of non-dendritic microstructure and the technologies for production of non-dendritic feedstock. In the second section, focus was drawn on CS casting process, the mechanism involved, and evolution of microstructure during CS casting process, its advantages and limitations. In the third section, particular emphasis was laid on the influence of process parameters on the microstructure of semi-solid Aluminum alloys during flow through CS and the optimum process parameters from the literature were discussed in detail. The fourth section deals with the reheating and isothermal holding conditions and the mechanical properties of semi-solid Aluminum alloys processed through CS route.

II. SEMI-SOLID METAL PROCESSING

Semisolid processing of alloys is a very important aspect of the present day manufacturing of automobile, aviation and marine components. Semisolid metal (SSM) forming, i.e., forming a metallic alloy at a temperature between its equilibrium liquidus and solidus temperatures, is a hybrid metalworking process combining elements of both casting and forming. The basic requirement of semi-solid processing is the slurry with nearly spherical primary α-Al particles [2-4].

A. Origin of SSMP

The discovery of shear thinning and thixotropic behaviour of partially solidified alloys under vigorous agitation in early 1970s was the starting point of SSMP [2]. During 1970s, Spencer, a Ph.D student under the supervision of Prof. M. C. Flemings, in M.I.T., Cambridge, MA, USA, was carrying out hot tearing tests on Sn-15% Pb alloy. In course of an experiment related to viscosity measurement of the semisolid alloy, shearing started above the liquidus temperature, and continued as the slurry was subjected to slow cooling through the mushy zone until solidification was nearly complete. Due to shear thinning, the viscosity of the slurry was reduced, such that it behaved like a fluid, and dendrite formation with accompanying solute segregation was prevented [1-2]. It was identified that the material which was cooled into the semi-solid state without stirring was dendritic as in Fig.1a, while the microstructure of the continuously stirred materials was spheroidal (i.e. consisted of spheroids of solid in the liquid matrix) as in Fig.1b. Thus, it was discovered that the semi-solid alloy with solid fraction of 0.4, and without a dendritic structure, behaves like a fluid with viscosity less than that of the olive oil. It was also found that the viscosity of semisolid alloy subjected to continuous agitation during cooling was significantly lower than that observed if cooling was carried out without agitation [2, 4-6].

B. Classification of Semi-solid Processing routes

Over the past four decades an extensive research and development has been dedicated to investigate the feasibility of SSM processing and a range of reviews are available on SSMP [3-6]. Semi-solid processing is broadly classified into two routes including the ‘rheocasting’ and ‘thixocasting’. The process of production of non-dendritic semisolid slurry by shearing during solidification is referred to as rheocasting as shown in Fig. 2a. Rheocasting was proposed as a process involving control of the rheological properties of the semisolid alloy [2]. During rheocasting, the semisolid alloy is agitated, leading to breaking up of dendrites. Thixoforming is a general term coined to describe the near net shape forming processes from a partially melted non-dendritic alloy slug within a metal die. If the component shaping is performed in a closed die, it is referred to as “Thixocasting”, while if the shaping is achieved in an open die, it is called “Thixoforging”, as schematically illustrated in Fig. 2b [4]. The thixoforming consists of three important steps as shown in Fig. 3.

(a) Production of feed stock with a globular microstructure
(b) Reheating the feedstock to semi-solid region
(c) Forming in the semi-solid region.

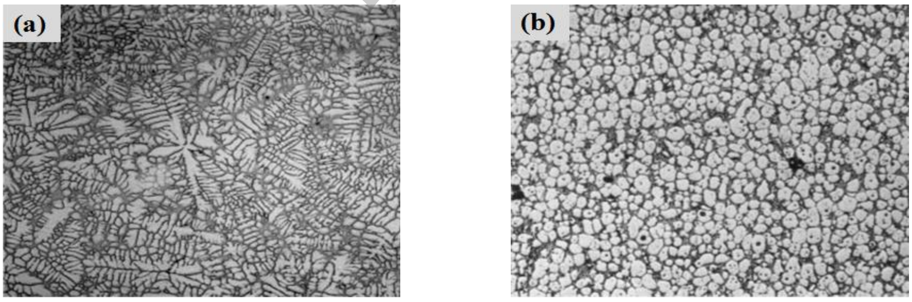

Fig. 1. a) Dendritic microstructure (b) Globular microstructure [6]

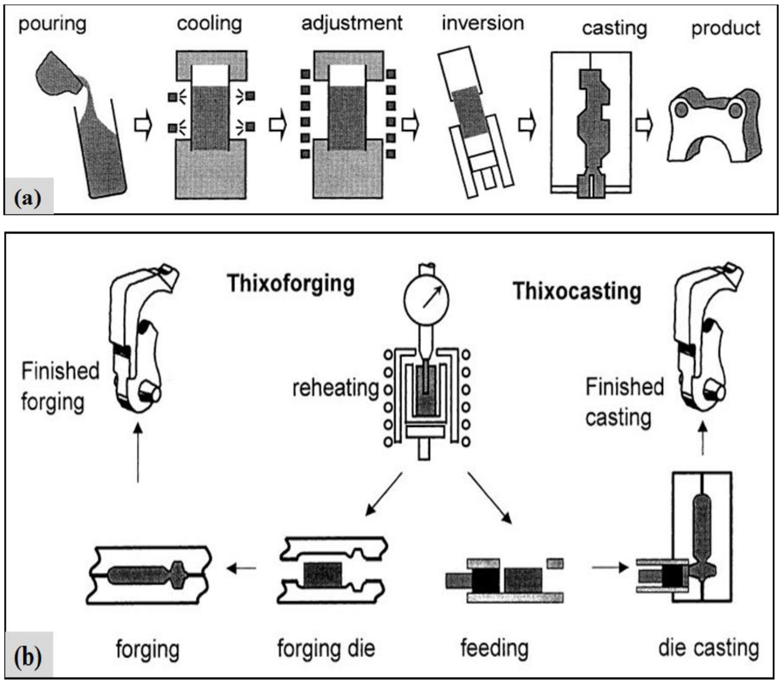

Fig. 2. Schematic illustration of (a) Rheocasting process (b) Thixoforming processes [4]

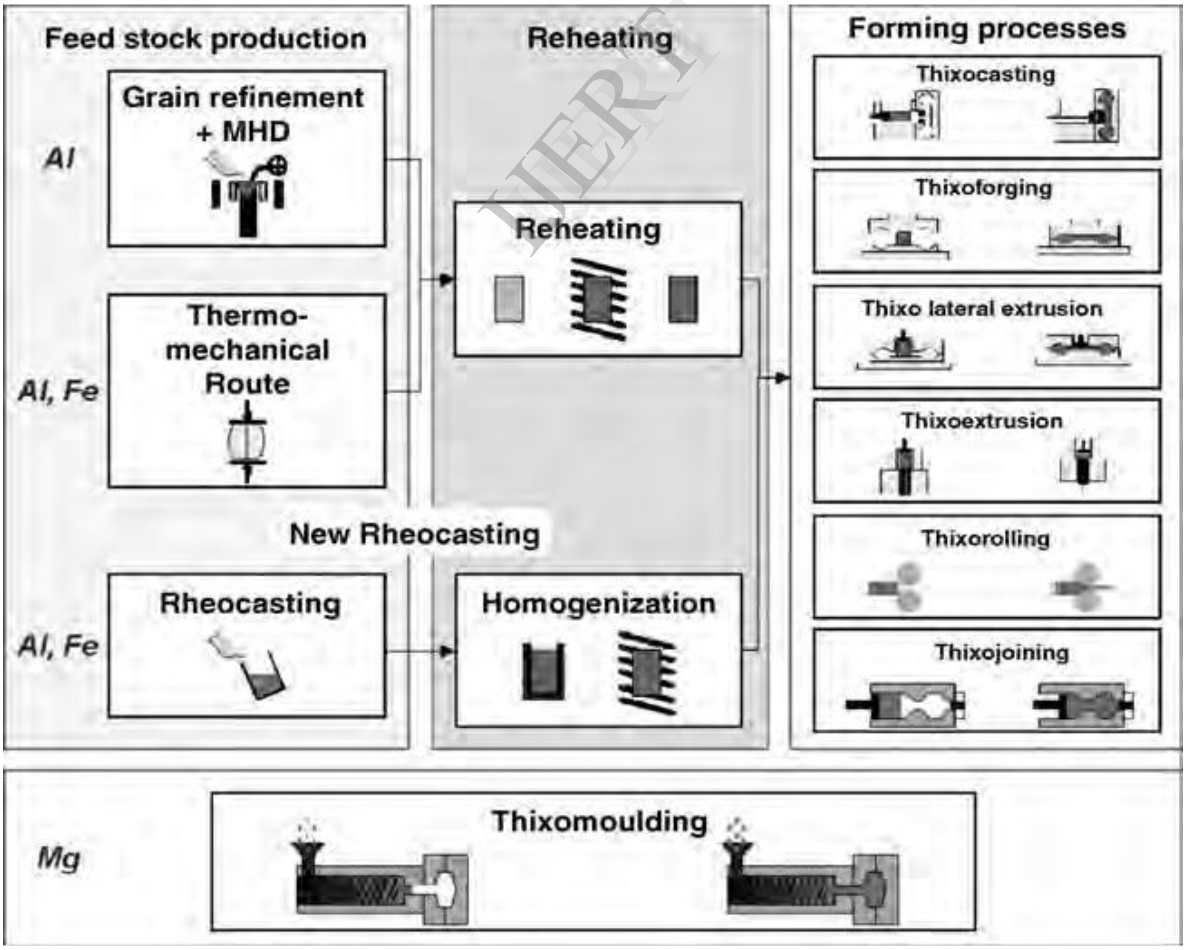

Fig. 3. Semi-Solid Metal Forming processing routes [16]

C. Rheological behaviour of semi-solid slurries

A lot of investigation by researchers [2-6] has already been done on the rheological characterization of semisolid alloys. The rheological behaviour of the semi-solid alloy is the flow behaviour between liquidus and solidus range and is strongly dependent on temperature and shear rate. Rheological behaviour is an important aspect for process control, and for the prediction of flow into die cavities during forming process. Roughly SSM slurries are classified into two broad categories: "liquid-like" slurries consisting of dispersed solid particles and behaving like a fluid under the influence of external forces, while "solid-like slurries" consists of interconnected solid phase and behaving like solid, exhibiting well defined yield strength [4]. Mechanisms of deformation in these two types of slurries are fundamentally different. The SSM slurries with solid fraction of 0.6 exhibit two unique rheological properties that is thixotropy and pseudo plasticity. Thixotropy describes the time dependence of transient state viscosity at a given shear rate, while the pseudo-plasticity refers to the shear rate dependence of steady state viscosity. All SSM processing techniques rely on either or both of these properties in the same process. Therefore, successful development of SSM processing technologies requires a good understanding of the rheology of SSM slurries.

D. Mechanisms for formation of non-dendritic microstructure

Several mechanisms have been proposed to explain the presence of non-dendritic morphology which involves the formation of fine near spheroidal particles through forced convection caused by stirring [2-4]. One mechanism, which distinguishes semi-solid metal slurries from other suspensions, is that the particle shape and size vary irreversibly with time. The mechanisms for dendritic fragmentation, which may be divided into major groups, as shown in Fig. 4.

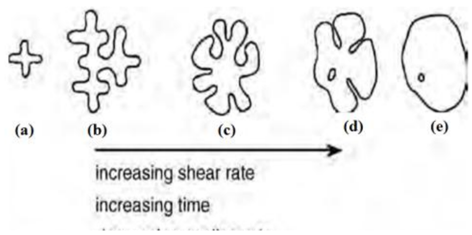

Fig. 4. Schematic illustration of evolution of structure during solidification with vigorous agitation: (a) initial dendritic fragment
(b) dendritic growth (c) rosette (d) ripened rosette (e) spheroid [4].

E. Production of non-dendritic feedstock

The objective of feedstock production is to provide a material with a characteristic thixotropic microstructure where a non-dendritic (or globular) primary phase with a fine grain size is uniformly distributed in a matrix of lower melting point [4]. The important routes for obtaining non dendritic feedstock [4] are: mechanical stirring, magneto-hydrodynamic stirring (MHD), strain induced melt activated (SIMA) process, spray casting, liquidus casting, chemical grain refining, ultrasonic treatment and cooling slope (CS) casting process. Despite the many methods developed, thixoforming has not enjoyed the wide spread application due to high production costs and limited choice of size and non-uniform microstructure of ingots from these technologies. Thus simple processes with reduced equipment and processing costs and with a flexible ingot size are required to overcome these adversities. One such route is the CS casting process which employs simple equipment and involves low running costs [7-9]. Therefore, this review is focussed on semi-solid processing of Aluminum alloys through cooling slope route and the optimum parameters to obtain a sound feedstock.

III. THE COOLING SLOPE CASTING PROCESS

One of the major factors that contribute to higher costs of the thixoforming process is the high costs associated for producing the specialized ingots required for thixoforming that possess non-dendritic or globular microstructures. Therefore research on the development of feedstock methods was pursued over the recent years, which allow the production of feedstock materials in a more cost efficient way. CS casting process is one of the technologies developed to produce the feedstock material which eliminates a major element of the costs in the thixoformed products [7-9].

A. CS Process

CS casting is a simple process which involves pouring molten metal with a suitable superheat through a cooling slope plate and subsequent solidification in a mould [7]. It is a recently developed method to produce raw material for further thixoforming processes. The cooling slope casting process is composed of the following main process sections as shown in Fig. 5.

a) A melting pouring section (1), which consists of a crucible which melts the alloy and pours down it through the cooling slope plate
b) A nucleation section (2), which generates crystal nuclei in the melt as it is flowing through the cooling slope plate
c) A crystal generating section (3) in which metal obtained from the nucleation section is cooled down in the metal mould.

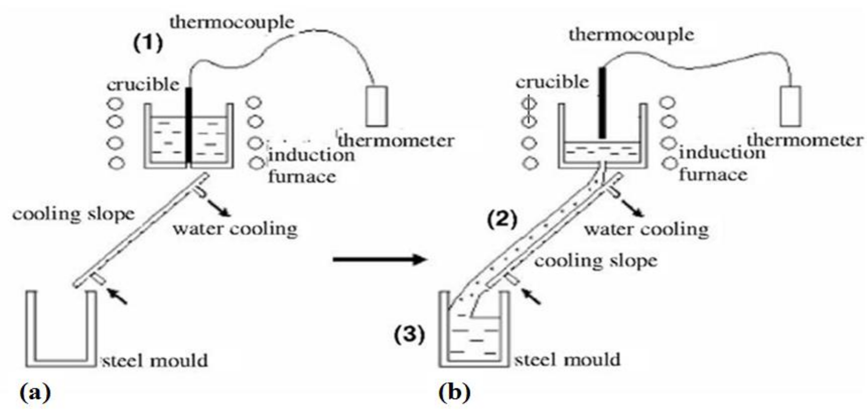

Fig. 5. Cooling slope casting process (a) melting (b) casting via the cooling slope [12]

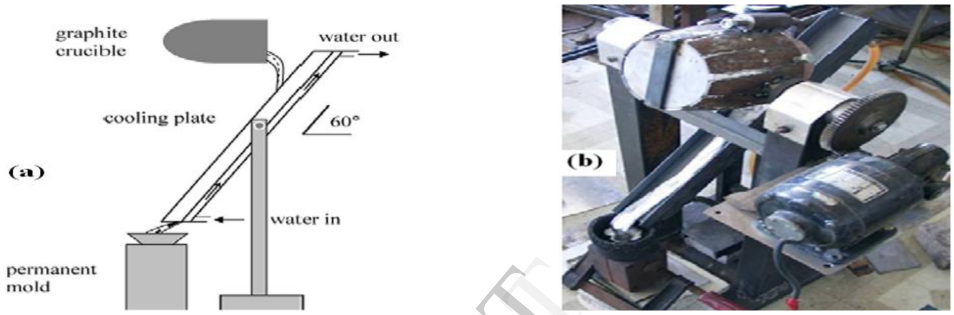

Fig. 6. Cooling slope casting unit (a) Schematic illustration (b) Experimental setup [17]

The essence of CS casting process setup [17] is a very simple water-cooled plate as shown in Fig. 6. In this work the cooling plate which was adjusted at 60° with respect to the horizontal plane was cooled with water circulation underneath. The A390 alloy feedstock for thixoforming was successfully produced at a temperature of 571°C, and the best microstructural features were obtained with a pouring temperature of 585°C and a cooling length of 300 mm.

B. Mechanisms involved in CS casting process

Two mechanisms have been suggested to explain the formation of non-dendritic microstructure during flow along CS casting process. According to Haga and Kapranos [8, 9] dendritic fragmentation mechanism plays an important role during microstructural evolution in CS casting process. The fragmentation of weak dendritic arms may occur near the contact surface of cooling slope samples because dendritic crystals in the partially solidified melt collide under gravitational forces on the inclined slope. These crystals, formed by detachment of weak dendrite arms along the cooling slope plate based on dendritic fragmentation mechanism, then grow in the mould.

On the other hand according to Motegi et al. [18] crystal separation theory is responsible for the formation of non-dendritic morphology in as-cast CS microstructures. Fig. 7a shows the mechanism of necking and detachment of crystals from mould walls which is known as “separation theory”. According to this theory, granular crystals nucleate and grow on the cooling slope wall and are washed away from the wall by fluid motion. They believe that metal crystals were generated on the cooling plate and moved with molten alloy into a heating mould, and subsequently become granular in the mould resulting in a fine globular microstructure [16]. The different growth rate in different regions of the solid surface is due to the temperature profiles in the liquid containing different gradients of solute concentration ahead of the solidification front, as shown in Fig. 7b. At higher gradient (roots of the crystal in contact with the cold surface), the reduction in the transformation temperature is higher which leads to smaller interface undercooling and as a consequence smaller growth rate.

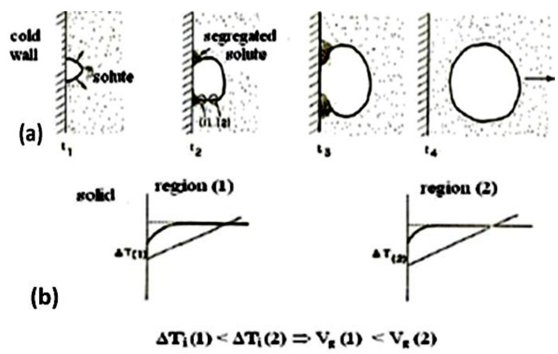

Fig. 7. (a) Schematic illustration of crystal separation mechanism of detachment of nuclei from the surface of the cooling slope (b) temperature profiles in the liquid in the

solidification front, for an alloy with partition coefficient (K) < 1 [18].

C. Microstructural evolution during flow along the cooling slope

The key step of semi-solid metal forming technology is an economical production of semisolid slurry with nondendritic microstructure. The primary crystals of the semisolid slurry processed through the cooling slope become spherical after being maintained in the semisolid state. During the process, solid nuclei are formed due to contact between the melt and cooling slope which cause rapid heat transfer. These nuclei are detached from the surface and finally distributed into the melt [7-10]. Matthias et al. [19] compared the microstructures of A356 alloy cast conventionally and by cooling slope casting process and reported that the later looks significantly different from that obtained by the former, even for the same cooling rates. The morphologies of A356 alloy processed by this group by conventional casting has a dendritic structure as shown in Fig. 8a, while that processed via CS process typically consists of globular grains as shown in Fig. 8b.

D. Advantages and limitations of CS casting process

The principal advantages of CS casting process are: (a) It uses a basic and attractive technology in which no special equipment is needed. It is a simple processing route and the equipment and running costs associated with the cooling slope are very low [7-9]. (b) The process provides globular or spheroidal microstructure when the cast alloy is heated to the semi-solid temperature which is desirable for isotropic mechanical properties and toughness [10, 16].

The limitations of CS casting process are: (a) formation of casting defects, such as pores and oxide, which would cause the mechanical properties of thixoformed cooling slope products to be lower [21]. (b) tendency of solidification shell formation on the surface of slope plate which may affect the morphology of primary α-Al phase [22].

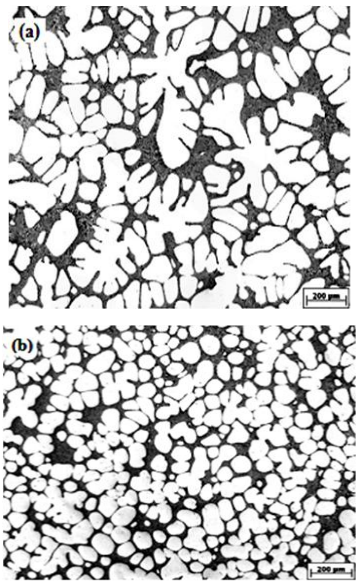

Fig. 8. Morphology of A356 Alloy (a) Conventionally cast (b) Cooling Slope Casting [19]

E. Studies on CS casting process in Aluminum based alloys and composites

1) Alloys

Extensive research on cooling slope process was initially carried out by Motegi and Haga in Japan. The initial version of cooling slope equipment was built by Prof. T. Haga at Sheffield University, UK. Motegi et al. [23] performed many experiments using a water cooled slope made of pure copper in order to obtain thixotropic Al-Si-Mg feedstock for thixoforming. They modified a vertical continuous casting machine as shown in Fig. 9.

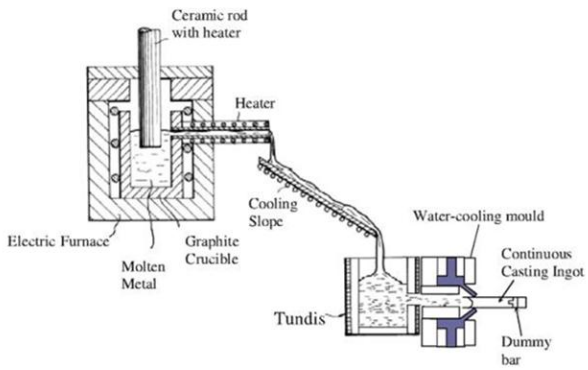

Fig. 9. Horizontal Continuous casting process of semi-solid aluminum alloy [18]

Crystals seeds of the primary α- aluminum were nucleated on a specially designed cooling plate. This was followed by pouring the molten alloy into the mould. The seeds of primary crystals existing in the molten alloy grew granular grains. In their first study, Al-7.64wt%Si-0.303wt%Mg alloy was poured at temperature ranging from 624 to 724 ^{o}C with a cooling plate of 470 mm long and 70^{o} inclination. They observed that granular crystals appear at pouring temperature of 654 ^{o}C and cooling length of 100 mm. They found that the cooling plate was effective in generating crystal seed in the molten alloy. They also found evidence that lower casting temperatures in the mould yield more granular crystals of α-aluminum.

In the following experiments, Motegi et al. [24] used a water cooled slope and poured Al-1.63wt%Si-0.54wt%Mg alloy on the slope at 656, 666, 676, 686, and 696 ^{o}C. They found that the cooling slope is useful for generating numerous crystals seeds, and the best conditions were tilt angle of 60^{o} and length 200 mm. If length of the cooling slope is too long, the molten alloy flowing onto it forms a solid shell. On the other hand, short distance generate small amount of crystals seeds because there are less position available for seed to be generated. It was concluded that finally the best pouring temperature was 656 ^{o}C. They found evidence that increase in pouring temperature resulted in a bigger particle size. Moreover, semisolid slurry must be held in an isothermally heating mould in order to produce granular crystals.

Haga and Suzuki [7] analyzed the factors which affect the spheroidicity of α-Al particles in ingots for thixoforming obtained by casting Al-6Si alloys via a cooling slope made of mild steel, at a temperature range of 640 to 680 ^{o}C. They reported that the cooling rate strongly affect the globularization of primary α-Al particles and obtained a small particle size. Later, Haga and Kapranos [9] produced A356 and A390 Aluminum alloy ingots via both cooling slope and low superheat casting. For the cooling slope process, they used two pouring distances 150 and 250 mm, with a tilt angle of 60°, and superheats of 20 and 40 °C. The low superheat casting was carried out with superheats of 10, 20 and 40 °C. For both experiments, copper and insulating moulds were used. The resulting ingots were reheated at 570, 580 and 590 °C and then thixoformed. The results from this work are only qualitative. With copper die, if the ingot was heated up to 570 °C the primary particles did not spheroidise, but if the temperature is 580 or 590°C the particles became spheroidal, with a larger particle size for the higher temperature. With the insulating die, when the ingot was heated up to 570°C the primary particles spheroidised (for 580 or 590 °C), with a larger particle size for the higher temperature. The primary crystals in the feedstock produced spheroidized when the material was reheated to the semisolid condition.

After the inventions made by Motegi et al. [23] and Haga et al. [7-9] on the cooling slope process, the use of a cooling slope to generate non-dendritic semisolid microstructures has gained attention among the researchers. Later, Yucel Birol has worked thoroughly on the production of thixoforming feedstock on semi-solid A357 aluminum alloy [10], hyper eutectic A390 alloy [17] and die-casting A365 alloys [25]. The dendritic primary phase in the conventionally cast A357 alloy [10] was readily transformed into a non-dendritic upon CS casting, cast over the cooling plate from pouring temperatures between 620 and 640 ^{o}C and with cooling lengths between 200 and 400 mm employed in their work. The dissipation of the melt superheat required longer cooling lengths for higher pouring temperatures. The primary phase in the ingots produced attained a globular morphology in 5 min during isothermal holding at 580 ^{o}C. The hyper eutectic A390 alloy feedstock produced with CS casting [17] with a pouring temperature of 585 ^{o}C and cooling length of 300 mm was thixoformed successfully at a temperature of 571 ^{o}C. They [17] found evidence that the thixoformed part thus produced was metallurgically sound, free from porosity and revealed a uniform dispersion of fine Si particles in a homogeneous matrix. Heat treating the thixoformed part to T6 temper produced a substantial increase in hardness. The thixoforming temperature employed in their work was much lower than the range of die casting temperatures (700-760 ^{o}C) used for A390 alloy.

The dendritic α-Al phase in case of A365 ingot readily transformed into a non-dendritic one upon casting over a cooling plate from a pouring temperature of 625 ^{o}C and with a cooling length of 400 mm as reported by Y.Birol [25]. It made possible to thixoform the slugs machined from the CS-cast A365 ingots in a laboratory press into a simple part after they were held for 5 min at 580 °C. However, the thixoforming process was very challenging since even the slightest deviation from 580 °C has either led to shape distortion of the slug or degraded its thixoformability, resulting in incomplete die filling in both cases. The thixoformed parts so produced attained hardness values as high as 84 HB after T6 heat treatment. H.Budiman et al. [26] examined the microstructure of CS casting of a commercial Al-Si alloy and compared the microstructures of cooling slope with and without water circulation and concluded that the water circulation influenced the fraction volume of α-Al particle, grain size and shape factor.

Recently, Das et al. [27] has studied the effect of slope angle and addition of grain refiner on microstructure evolution of the solidifying melt of A356 alloy through rheocasting process employing CS casting route. The pouring temperature and cooling length of the channel in their experiments were kept fixed at 650 °C and 500 mm respectively. They observed that for the case using a cooling slope, the primary phase becomes more globular with increasing slope angle and hence increasing shear. Liu et al. [12] used CS casting technology for the preparation of thixoformable feedstock from Aluminum wrought alloys instead of conventional cast alloys. They poured 2014, 6082, 7075 and 7010 Aluminum wrought alloys at a temperature 10-20 °C above the liquidus via a water cooled slope and reheated as-cast samples to the semi-solid intervals in order to observe the morphological evolution. They reported that cooling slope cast material showed coarsened rosette morphology with a relatively high proportion of entrapped liquid within globules after heating to the semi-solid state.

2) Metal Matrix Composites

Semisolid metal processing of metal matrix composites with equiaxed microstructures via cooling slope casting is gaining popularity. Qin et al. [31] investigated the semisolid microstructure of Mg_2Si/Al composite by cooling slope and reported that the morphology of primary Mg_2Si and α-Al grains in the composite are globular and/or elliptic after partial remelting process. H. Budiman et al. [28] produced A356/Al_2O_3 composites and found that conventional stir cast composite has fully dendritic microstructure in contrast to equiaxed morphology of the cooling slope cast samples. They also found that microstructure exhibits finer α-Al grains and greater shape factor than the conventional composites. Z.Chen, et al. [29] conducted experiments by employing a cooling slope technique to produce semisolid slurry of *in-situ* Al-12Si -3wt%TiB_2 composites fabricated by flux assisted synthesis method. They reported that the minute TiB_2 particles with size 0.2-0.5 µm uniformly distribute in the spherical α-Al grains and at the boundary of eutectic Si. Results have shown that α-Al grain is spherical with an average grain size of 47.4 µm. The experimental results of G.S. Gan et al. [30] on wrought aluminum 7075 alloy based *in-situ* TiB_2 composite shows that *in-situ* TiB_2 particles and serpentine channels are beneficial to increase the number of solidification nuclei and promote uniform distribution of α-Al nuclei. They successfully produced semi-solid 7075-3TiB_2 slurry with globular grains.

Based on the previous research reports it is clear that the dendritic primary crystals of the semisolid slurry at the cooling slope transforms into non-dendritic and become spherical after being maintained in the semisolid state. CS casting process to generate non-dendritic semisolid microstructures is gaining increasing attention among the researchers across the globe, which indicates CS processing can be a potential route to produce feed stock material of both alloys and metal matrix composites with high mechanical properties suitable for thixoforming operations.

IV. EFFECT OF PROCESS PARAMETERS ON CS CAST FEEDSTOCK

There are several key process parameters such as mould material, mould temperature, cooling slope length, cooling slope angle, superheat, pouring temperature etc. which directly influence the final microstructure of the solidified slurry during cooling slope processing [32]. Some of the important process parameters in the cooling slope process are discussed in the following subsections:

A. Effect of mould material and mould condition

E. C. Legoretta, et al. [32] in their investigations on development of thixotropic feedstock of A356 alloy by cooling slope process, poured the slurry into a vertical mould of four different materials i.e copper, mild steel, stainless steel and insulating moulds. They reported that pouring the slurry at superheat of 35 °C, the mild-steel and copper gave the highest cooling rates, whilst stainless steel gave an intermediate rate and the insulating mould the lowest rate. In this case, above the solidus temperature of 577 ^{o}C, the cooling rates for all except the insulating mould were very similar. In contrast to this, when the slurry was poured at room temperature into the four different cold moulds, then a high thermal conductivity mould gave a smaller primary particle size in the centre (65 µm for the copper mould) whilst the primary crystals in the centre of the insulating mould were much larger (135 µm). Similar results on the effect of mould material was shown by Haga and Suzuki [7] that when the thermal conductivity of the mould material is high, the cooling rate of the ingot becomes high, and as a result the size of the primary crystal of the ingot cast into a metallic mould becomes smaller than that cast into an insulator mould. The mould condition also has an effect on the microstructure. The results obtained by E. C. Legoretta et al. [32] by pouring the slurry into a cold mould were compared with those from pouring into a stainless steel mould, at 300 ^{o}C and 400 ^{o}C, showed that with increased mould temperature, the microstructure becomes coarser but not spheroidal. However, if the mould and melt are maintained in a furnace at a semisolid temperature, even for a short time, the microstructure becomes spheroidal and homogeneous.

B. Effect of pouring temperature

The pouring temperature has the greatest influence on microstructure of semi-solid Aluminum alloys. The fine α-Al grains and their sphericity play an important role for thixoforming experiments [45]. It has been previously reported by Legoretta et al. [32] that the superheat has a maximum effect on particle size and shape factor. They gave evidence that shape factor in the centre of the A356 alloy ingot varied between 1.4 for a pouring temperature of 620 °C (i.e. strongly spheroidal) to 2.6 for 680 °C (i.e. predominantly dendritic). At the surface of the ingot, low superheat gave a much finer microstructure in comparison with higher pouring temperature. Similar trend was also reported by Cardoso et al. [43] that low pouring temperatures promote spheroidal morphology of the α-Al phase and longer holding times in the semisolid condition improve the spheroidicity of these particles.

N. Saklakoglu et al. [46] in their experiments on A380 alloy observed that dendritic structures were markedly changed under the CS casting method. They reported that pouring the metal via cooling slope with a low superheat (615 °C) resulted in globular structures, whereas for the medium superheat (630 °C) the particle morphology was a mixture of globular and rosette-like, and at high superheat (650 °C) a mixture of rosette-like and coarse dendritic structure. Jun. Xu et.al [36] reported similar observation on A356 alloy that lowering the pouring temperatures changes the microstructure from dendritic to fine spheroidal structure. P. Das et.al [39] developed a numerical model and simulated the liquid metal flow of A356 alloy through cooling channel using Eulerian two-phase flow approach and investigated the effect of pouring temperature on cooling channel semi-solid slurry generation process. They reported that of three different pouring temperatures (687 °C, 672 °C and 650 °C), 650 °C yielded the best results.

C. Effect of length of cooling slope

The length of the cooling slope directly affects the cooling-shearing time on melt, which affects the microstructure of semi-solid melt. Haga and Suzuki [7] reported that a slope length of 300 mm yields globular primary crystal as compared to 100 mm slope length. F.Taghavi, et.al [33] on their observations on the effects of length on the thixotropic microstructure of A356 Aluminum alloy, found that there was an optimum length in which minimum grain size and maximum sphericity can be achieved, at a constant angle. At slope angles of 40° and 50°, increase in the length of inclined plate from 200 mm to 400 mm led to better grain refinement with the size of α-Al phase changing to 28-32 µm and its shape factor improving to 0.67-0.70. Motegi et al. [24] reported that if the slope length is too long, the slurry could form a solid shell on the slope. On the other hand, if it is too short, nucleation sites may be insufficient. Thus, optimum pouring length, promotes the transformation of coarse dendrites into rosette shape grains by increasing the cool-shear time [45].

D. Effect of angle of inclined plate

The inclination of the cooling slope governs the flow rate and contact time between the molten alloy and the cooling plate. Jun. Xu et.al [36] demonstrated the effect of angle on microstructure of A356 alloy and showed that increase of the angle of cooling slope from 30° to 45° led to decrease of size of α-Al phase from 71 µm to 65 µm and the shape factor of α-Al phase from 1.8 to 1.4. Further, when the angle was increased from 45° to 60° the size and shape factor of α-Al phase was increased to 85 µm and 2.2 respectively. F.Taghavi, et.al [33] investigated the effects of various angles

(30°, 40°, 50°, 60°) of inclined plate on A356 alloy. They found that applying inclined plate at 30° cannot eliminate dendritic morphology of α-Al phase in microstructures while angles of 40° and 50° led to the elimination of dendrite microstructures, and globular microstructures are replaced for all lengths. But, increase in the angle from 50° to 60° led to increase in the size of α-Al phase.

Recently, R. Ritwik et al. [41] worked on the rheological behaviour of melt along the cooling slope and reported that the flow regime of the mush in the low-convection cooling slope processing primarily depends on the inclination of the slope. Moreover, the evidence from remnant works suggests that the lower plate angle could not eliminate the dendritic morphology of the α-Al phase in the microstructures and the molten alloy flows slowly and a solid shell forms easily on the cooling plate [20]. In contrast, as the plate angle increases beyond the optimum angle, the time that the molten metal spent in contact with the inclined plate reduces, the alloy flows faster which results in less fracture of the dendrite arms and heat transfer between the melt and the surface of the inclined plate, which in turn causes less nucleation. Thus an optimum plate angle governs the flow rate and contact time between the molten alloy and the cooling plate which causes an increase in the shear stress intensity and leads to dendritic fragmentation.

E. Other CS casting process parameters

Besides the key process parameters such as pouring temperature, cooling slope angle and cooling slope length, it has been suggested that vibrating the cooling slope can result in finer grain size. Application of rotating mould to cooling slope gives the microstructure with finer grains and smaller shape factor [32]. The experimental results of S.Gencalp and co-workers [34] on A380 alloy suggests that the application of vibration on the cooling slope increases the nucleation and led to more breaking of dendrite arms into finer grains. Haga [42] used a melt drag twin roll caster (MDTRC) equipped with a cooling slope and produced strips of A356 alloy and gave evidence that semisolid strip casting enhances the mechanical properties. Dhindaw et al. [44] investigated the microstructural features and microsegregational behaviour for Al-base alloys studied, under low and moderate shear rates during rheo processing and concluded that the microstructures of the primary pre-quench solid for stir-cast samples resulted in rosette or spheroidal morphologies. In order to avoid or reduce the solidification shell, J. Xu et al. [36] reported that coating on the surface of the cooling slope with a nitride dope can effectively reduce the formation of solidification shell.

More recently, Haga et al. [35] devised a cooling roll and suggested that cooling roll is useful to prevent adhesion of the solidified metal. Yang and Mao [21] investigated the integral

microstructure of semisolid A356 alloy slurry with larger capacity cast by serpentine channel and reported that ideal slurry with larger capacity can be prepared through serpentine channel with good cooling ability. Sunitha et al. [38] reported that rosette or globular structures were possible to obtain with low shear rheocasting. This was attributed to the heat and solute transport due to the convection induced by the shearing and breaking down the dendrite arms by shear stress. Das et al. [40] suggested that grain refiner addition also aids to reduce grain size with improved sphericity of the primary α-Al particles in the as cast microstructure of the rheocast billets. Significant increase in % elongation and strength were observed after grain refinement.

Table I summarizes the process parameters involved in the production of feedstock via CS process in Aluminum alloys and its composites. As can be seen, a host of process parameters are involved in the production of a cast feedstock material with desired microstructure. Therefore the challenge lies in judicious choice of right process parameters to obtain a sound feedstock.

V. REHEATING AND ISOTHERMAL HOLDING CONDITIONS FOR CS CAST FEEDSTOCK

Reheating the alloy to semi-solid state is particularly an important step in the thixoforming process. It has been reported that the feedstock produced by CS casting provides globular or spheroidal microstructure when the cast alloy is reheated to the semi-solid temperature which enhances the mechanical properties [10,24]. To achieve this globular microstructure, the important processing parameters during the reheating process include accuracy and uniformity of heating temperature and heating duration. It is the heating temperature that determines the solid fraction of the slug. Too high a heating temperature causes instability of the slug resulting in difficulties of slug handling, while too low a heating temperature leads to unmelted phases in the slug leading to detrimental effect on the rheological properties during die filling and consequently on the ductility of finished parts. A small variation in temperature can cause a large difference in solid fraction. Therefore accuracy and uniformity of heating temperature is of prime importance. Finally, the heating duration has to be optimised; too long a heating time will cause structural coarsening, while too short a heating time will lead to incomplete spheroidization of solid particles. Thus, there is a need to arrive at optimum reheating parameters of the semi-solid Aluminum alloys processed via CS casting. There is very few data available on mechanical properties of thixoformed parts processed by CS route as opposed to those processed by other methods. Table II summarizes the mechanical properties of thixoformed alloys processed by CS casting and optimum reheating parameters.

TABLE I. OPTIMUM PROCESS PARAMETERS USED IN COOLING SLOPE CASTING PROCESS OF SEMI-SOLID ALUMINUM ALLOYS AND COMPOSITES

Aluminum alloy	**Processing conditions**	**Mould material**	**Slope Angle (in degrees)**	**Cooling Length (mm)**	**Pouring Temperature (°C)**	**Grain size of α-Al (µm)**	**Shape Factor of α-Al**	**Reference**
Al-6Si	-	Mild Steel	60°	300	640	-	-	[7]
ZAlSi9Mg	Vibrational Cooling Shear slope; Vibration Frequency optimum at 50Hz	-	60°	600	600	50	0.71	[45]
Al-Si	-	Stainless Steel	60°	250	620	29	2.92	[26]
Al-9Si-2Cu	Copper mould in water Bath	Copper	30°	1000	670	-	1.60	[22]
Al-6.05% Cu	Slope based		25°	1000	620	-	-	[44]
Al-1.63wt%Si-0.54wt%Mg	-	Water cooled mould	60°	200	656	-	-	[24]
A356	-	Mild Steel	60°	500	650	38	0.75	[27]
A356	-	Copper Mould in water Bath	45°	500	650	61-65	1.40	[36]
A356	Cooling Serpentine channel was used	Stainless Steel	-	-	680	-	-	[37]

TABLE I. CONT.

Aluminum alloy	**Processing conditions**	**Mould material**	**Slope Angle (in degrees)**	**Cooling Length (mm)**	**Pouring Temperature (°C)**	**Grain size of α-Al (µm)**	**Shape Factor of α-Al**	**Reference**
A356	-	Mild Steel	60°	200	620	-	-	[35]
A356	Cooling Channel Process	Ceramic	-	-	630	97	0.79	[19]
A356	Cooling slope	Mild Steel	40°	400	680	28	0.7	[33]

	Plate (copper)							
A356	Pipe consisting of partial inclined and partial vertical sections	Stainless Steel	optimum Slanted angle of inclined section 30^o	Height of partially inclined section 100	645	-	-	[21]
A356	-	Stainless Steel	60^o	200	630	70	1.4	[32]
A356	Melt Drag Twin Roll Caster (MDTRC) Copper roll equipped with mild steel cooling Slope	-	60^o	300	620	50	-	[42]
A356	-	-	60^o	250	620	-	-	[8]
A356	-	-	60^o	250	630	-	-	[9]
A356	New Rheo-casting (NRC) Process	Cold Steel	-	200	620	80	1.5	[43]
A356	-	metallic	60^o		620	-	-	[18]
LM25 (A356) Na-Modified	-	Graphite	20^o	2000	650	-	0.61	[38]
A365 (AlSi9MgMn)	-	Mild Steel	60^o	400	625	-	-	[25]
A357	Cooling slope (CS)	Mild Steel	60^o	400	640	65	1.4	[10]

TABLE I. CONT.

Aluminum alloy	**Processing conditions**	**Mould material**	**Slope Angle (in degrees)**	**Cooling Length (mm)**	**Pouring Temperature (°C)**	**Grain size of α-Al (μm)**	**Shape Factor of α-Al**	**Reference**
A380	Cooling slope Casting under vibration Frequency at 5.75Hz Reheating at 567°C for 5 min.	Mild Steel	60°	500	630	-	0.892	[34]
A380	Cooling slope	Mild Steel	60°	350	615	47.3	0.879	[20]
A390	-	Mild Steel	60°	250	630	-	-	[9]
A390	-	Mild Steel	60°	300	585	-	-	[17]
7075	Cooling slope with serpentine channel	Stainless Steel	-	390 (length of serpentine channel)	655 (After flow through one graphite serpentine channels)	23	-	[30]
Aluminum based Composites	**Processing conditions**	**Mould material**	**Slope Angle (in degrees)**	**Cooling Length (mm)**	**Pouring Temperature (°C)**	**Grain size of α-Al (μm)**	**Shape Factor of α-Al**	**Reference**
$A356\text{-}Al_2O_3$ Composite (% vol Al_2O_3)	-	Mild Steel	60°	250	-	55-65	0.75-0.8	[28]
$Al\text{-}Mg_2Si$ Composite	Aluminum slope is used	Steel	60°	-	-	50	0.69	[31]
Al-12Si-3wt%TiB_2 Composite	-	Copper	-	-	680	28.7	-	[29]
7075 – 3wt%TiB_2 Composite	Cooling slope with serpentine channel	Stainless Steel	-	390 (length of serpentine channel)	670 (After flow through two graphite serpentine channels)	26	-	[30]

TABLE II. OPTIMUM REHEATING CONDITIONS AND MECHANICAL PROPERTIES OF THIXOFORMED ALUMINUM ALLOYS PROCESSED VIA COOLING SLOPE CASTING PROCESS

Alloy	Process and Heat Treatment condition	Hardness	Yield Stress (MPa)	UTS (MPa)	% Elongation	Reference
A356	Rheocasting and T6 treatment	-	241	310	18	[8]
A356	Rolling and T6 Treatment	-	-	270	18	[42]
Al-6Si alloy	Cold Rolling, Reheating at 600 °C	-	-	160	13	[7]
A356	CS casting using copper Die; Thixoforming and T6 treatment	-	234	293	15	[9]
A390	CS casting and T6 treatment	-	234	320	1.6	[9]
A380	CS casting and Isothermal Treatment at 565 °C for 5 min.	-	-	-	-	[46]
A380	CS casting under vibration frequency at 5.75Hz ; and Reheating at 567 °C for 5 min.	-	-	-	-	[34]
A357	CS casting, Reheating at 580°C and Isothermal Holding for 5 min	-	198	245	14	[10]
A365 (AlSi9MgMn)	CS casting Reheating at 580 °C for 5 min.; Thixoformed and T6 Treatment	[1]57.9 ± 1.1 HB [2]84 HB	-	-	-	[25]
A390	CS casting Reheating at 571±1 °C for 5 min.; Thixoforming and T6 Treatment	[1]90 ± 4 HB [2]144 ± 3 HB	-	-	-	[17]
A356	Rheocast at Slope Angle 60° (Grain refined)	-	-	159	9	[40]
LM25 (A356) Na-Modified	Shear cast at 20° Solution Treatment at 540 °C Aged at 12h at 150 °C	100 ± 3 HB	-	196	12.6	[38]

Note: [1]As Thixoformed state; [2]After T6 Heat Treatment

VI. CONCLUSIONS

An extensive review of the literature on Cooling slope casting of semisolid Aluminum alloys suggests the following:

(1) The cooling slope casting process is a simple and cost effective way of producing non-dendritic or globular microstructure in a single step.
(2) The advantage of the process lies in its simplicity and ease with which segregation and porosity can be minimized in the feedstock.
(3) The greatest challenge lies in the judicious selection of key process parameters such as pouring temperature, cooling slope angle and cooling slope length which dictates the final microstructure of the feedstock.
(4) Besides, reheating and isothermal holding temperature, and time of holding in the semisolid region need to be carefully optimized in order to obtain a sound thixoformed component.
(5) The cooling slope technique has immense potential to produce feed stock material with globular microstructure in not only cast Aluminum alloys but also in wrought Aluminum alloys and corresponding Aluminum metal matrix composites.

The authors believe that semisolid metal processing via cooling slope processing will be an important manufacturing process in many sectors in the immediate future.

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