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Development of Vibrating Cooling Slope (VCS) Method for Enhancing a Globular Structure in Aluminum A356 Alloy

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The globular structures formed during semi-solid processing of alloys make this technique unique for effective process control and property enhancement. Cooling slope casting is a simple but two-stage semi-solid process requiring re-heating to semi-solid region to exhibit a globular structure. Mechanical vibration to a solidifying melt can also lead to grain refinement and formation of a globular structure. However, this technique is confronted with the difficulty of long processing time. In the present study, a new process, termed Vibrating Cooling Slope (VCS), developed at Tehran University is described in which the conventional cooling slope and vibration casting methods have been combined into an integrated one for producing globular structures in the as-cast condition. The VCS technique has been applied to A356 aluminum alloy and the effect of vibration frequency (in the range of 50 -70 Hz) on the microstructure of the solidified alloy was investigated. The result showed that while the samples made by the still cooling slope converted to a globular structure only after re-heating treatments, the VCS processed samples exhibited a globular structure in the as-cast condition. It was also concluded that by increasing the vibration frequency, the size of globules was reduced and their morphology became more spherical.

Keywords: *Semi-solid processing, A356 aluminum alloy, Vibrating Cooling Slope, Vibration frequency, Size and morphology of globules.*

1. Introduction

Semi-solid metal processing, (SSP) is a relatively new technology for near-net-shape production of engineering components in which metal alloys are processed at a temperature above their solidus but below their liquidus. The critical characteristics of semi-solid alloys are their globular and non-dendritic structures formed during solidification enhancing unique features and beneficial properties compared with conventional metal forming methods [1-4]. One of the most popular SSP methods is cooling slope casting which benefits from a simple technology as compared with other alternative techniques [5-7] . In this process, molten metal is poured from the top of a tilting cooling plate and is accelerated and sheared by gravity. The semi-solid slurry is then solidifies and re-heated at a temperature within the freezing range of the alloy to generate a globular structure. It has also been documented that applying ultrasonic or mechanical vibration to a solidifying melt can lead to grain refinement of the alloy and formation of a non-dendritic and globular structure [8,9]. However, this technique is confronted with the difficulty of long processing time. To overcome such shortcomings, a new process, termed Vibrating Cooling Slope (VCS), has been developed at Tehran University in which the conventional cooling slope casting and vibration casting methods have been combined into an integrated one for producing globular structures. In this technique, there is no need to reheat the samples or provide a prolong vibration as are necessary for those parent methods, therefore eliminates capital cost expenditures, reduces the number of steps required, and hence reduces the costs of making components with a globular structure.

In the present study, a cooling slope assembly was designed which could vibrate mechanically in the vertical direction by the aid of an electrical motor. The cooling slope length was 400 mm and its angle was set to 45°. The influence of vibration frequency (40-70Hz) at a constant amplitude of 400 μm on the size and morphology of the resultant globules was investigated.

2. VCS device and experimental procedures

The vibrating cooling slope apparatus consists of a cooling slope made of copper plate (1000*120 *10mm) mounted on a steel frame. This assembly was fixed on a steel plate mounted on a table via four springs. A steel shaft was attached to this plate via two ball bearings. This shaft could rotate by means of a 3HP, 2840 rpm electrical motor via two pulleys and a belt. A 2Kg steel hammer was attached to the shaft through a hole which was drilled on it at an acentic position so that it could generate a vertical vibration during rotation. The vibration frequency could be altered by means of changing the rotation speed of the shaft by using different sized pulleys. The cooling slope surface was coated by boron nitride and for the present set of experiments its adjustable angle was set at 45º. Fig. (1-a) presents the general view of the VCS apparatus.

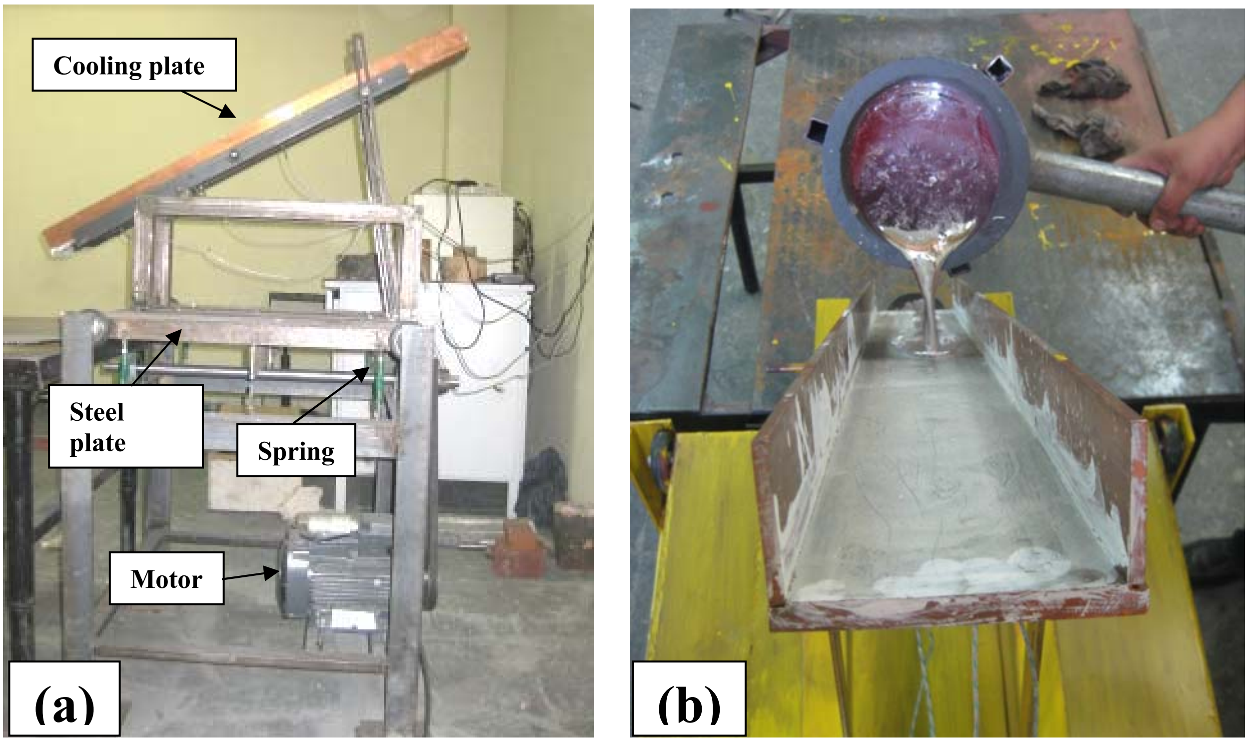

Fig. 1. Photographs showing (a): the general view of the VCS apparatus and (b): pouring the melt on the vibrating cooling slope.

In this study, aluminum alloy 356 of nominal compositions (in wt.%) of Al-6.93Si, 0.23Mn, 0.26Zn, 0.38Mg, 0.25Cu, 0.44Fe was used. About 1000 g of this alloy was charged in a clay-bonded graphite crucible and melted using an electrical resistance-heated laboratory furnace. The temperature of the melt was raised to about 650 °C and the molten alloy was poured on the surface of the slope plate which was vibrating at a pre-determined frequency within the range of 40 -70 Hz at a constant amplitude of 400 μm. The melt was poured onto a cooling slope set at 45° inclined angle, and 400 mm in length and cast into a steel mould (80 mm internal diameter and 60 mm in height) (see Fig.1-b). Our previous investigations revealed that at 45° and 400 mm, theA356 aluminum alloy exhibited the optimum degree of nodularity together with a uniform distribution of primary crystals [10].Therefore, we selected the same processing parametres for the present set of experiments. Also gravity casting in the same mold as well as conventionally cooling slope casting were carried out without vibration for the purpose of comparison. Four samples were cut from the geometrical centre of the solidified ingots as shown in Fig. 2. The smples generated by the still cooling slope as well as the gravity cast specimens were subjected to heat treatment at 585°C for 9 min followed by water quenching [11]. The as-cast samples generated by VCS process as well as the re-heated samples were subjected to standard metallographic procedures and etched in Keller's etching reagent (2 ml HF, 3 ml HCl, 5 ml HNO_3 and 90 ml H2O) for 15 s according to ASTM E407-(1994) standard method. The microstructure of samples was studied using an "Olympus-BX60M" light microscope. For image processing of the resulted microstructures, for each sample, a total number of 100 randomly selected globules were analyzed using "Clemex" software with the total measured area of 300 mm^2 per specimen.

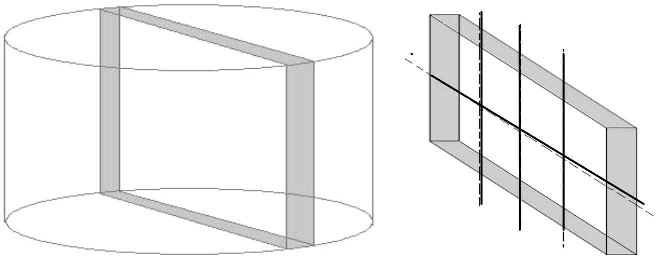

Fig. 2. The position of metallograpic samples in the ingot.

The effective diameter (D_e) and shape factor (SF) of the globules were calculated according to the following equations:

$$D_e=4A_g/P_g \tag{1}$$

$$F=4A_g\pi/P_g^2 \tag{2}$$

where (P_g) and (A_g) are the perimeter and surface area of the globules respectively. The standard deviation values obtained for each measurement was used for estimating the experimental errors.

3. Results and discussion

Fig. 3a shows the as-cast optical microstructure of the gravity cast A356 alloy demonstrating a coarse dendrite structure of the primary phase in the matrix. The microstructure of this sample after partial re-melting as shown in Fig. 3b reveals that the re-heating treatment did not have any considerable effect on the dendritic structure of this sample.

Fig. 4a shows the as-cast optical microstructure after conventional cooling slope casting of the A356 alloy. This microstructure consists of almost equiaxed α-Al particles dispersed in the eutectic matrix. Fig. 4b shows the structural evolution of this sample during partial melting. It can be seen that a globular structure is formed.

In the cooling slope process, solid nuclei formed due to contacting between the melt and slope plate cause rapid heat transferring. These nuclei are detached from the surface as a result of applying shear stress and melt flow. Finally they are distributed into the melt and generate a fine microstructure (Fig. 4a). It can be assumed that the applied shear stress on the slurry was not sufficient to globularize the structure. However, the primary crystals of the ingot became globular when it was re-melted into the semisolid state (Fig. 4b).

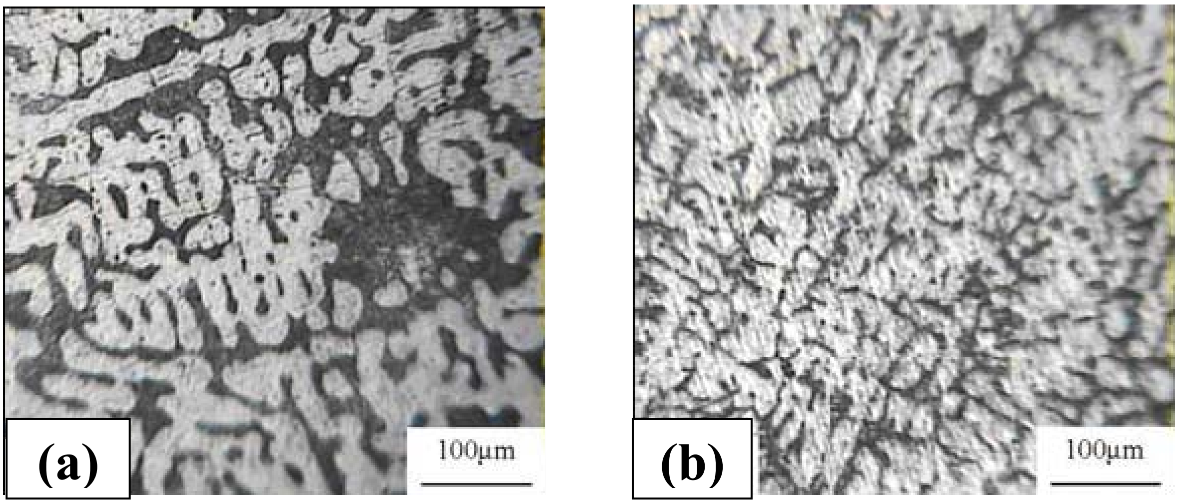

Fig. 3. Microstructure of A356 aluminum alloy obtained by conventional gravity casting in (a): the as cast condition and (b); after re-heating.

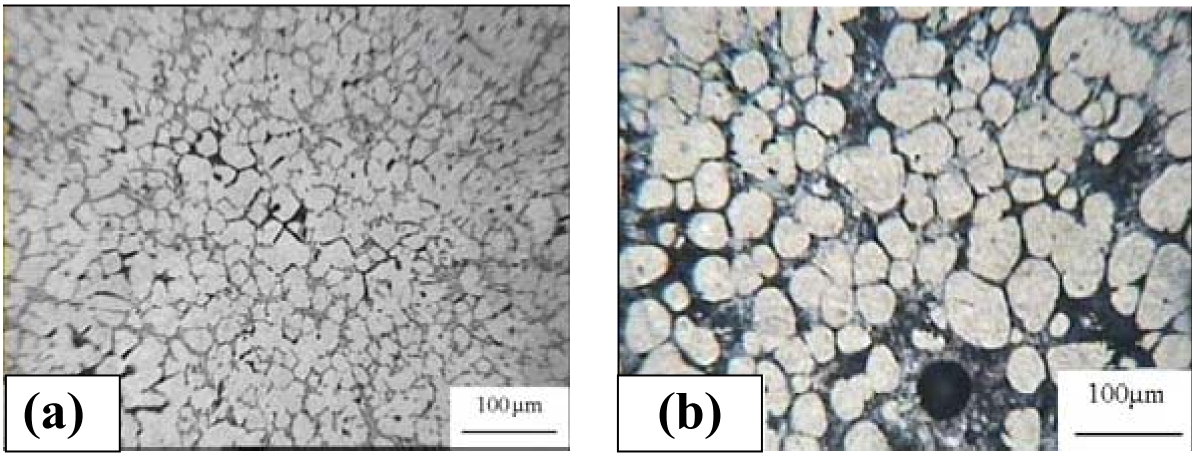

Fig. 4. Microstructure of A356 aluminum alloy obtained by conventional cooling slope in (a): the as cast condition and (b); after re-heating.

The microstructure of as-cast ingots that were cast by the VCS apparatus operated at the constant 400 μm amplitude and variable frequencies ranging from a smallest value of 40 Hz to a maximum of 70Hz are shown in Figs. 5a-d. It can be seen that, regardless of the vibration frequency, globular structures was attained for all the applied frequencies. The variation of the effective diameter (D_e) and shape factor (SF) of the globules as a function of the vibration frequency for the as-cast VCS processed samples are shown in Figs.6(a and b). The results obtained after re-heating of the samples cast by using the still cooling slope are also shown on these plots. It can be seen that increasing the vibration frequency results in the decreased size and increased globularity of globules. It is interesting to note that vibrating the cooling slope even at the lowest frequency of 40 Hz generates smaller sized and more spherical globules as compared with the non-vibrated specimens. These results can be explained by considering the combined effects of using a cooling slope and application of vertical vibration on the solidifying alloy before entering the mold cavity.

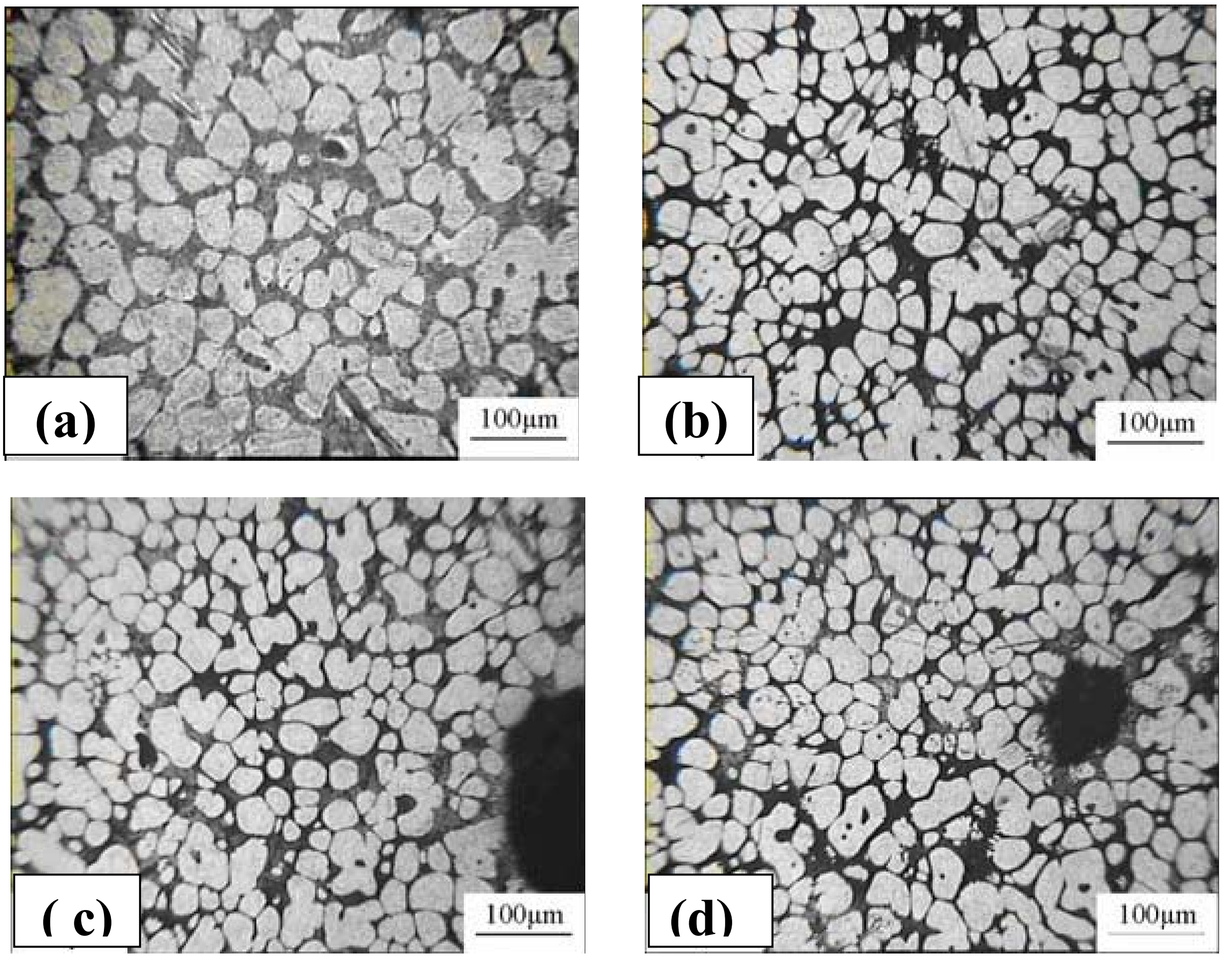

Fig. 5. Microstructure of the as-cast A356 aluminum alloy obtained by vibrating cooling slope vibrated at a constant amplitude of 400 μm and different frequencies of (a): 40, (b): 50, (c): 60 and (d) 70 Hz.

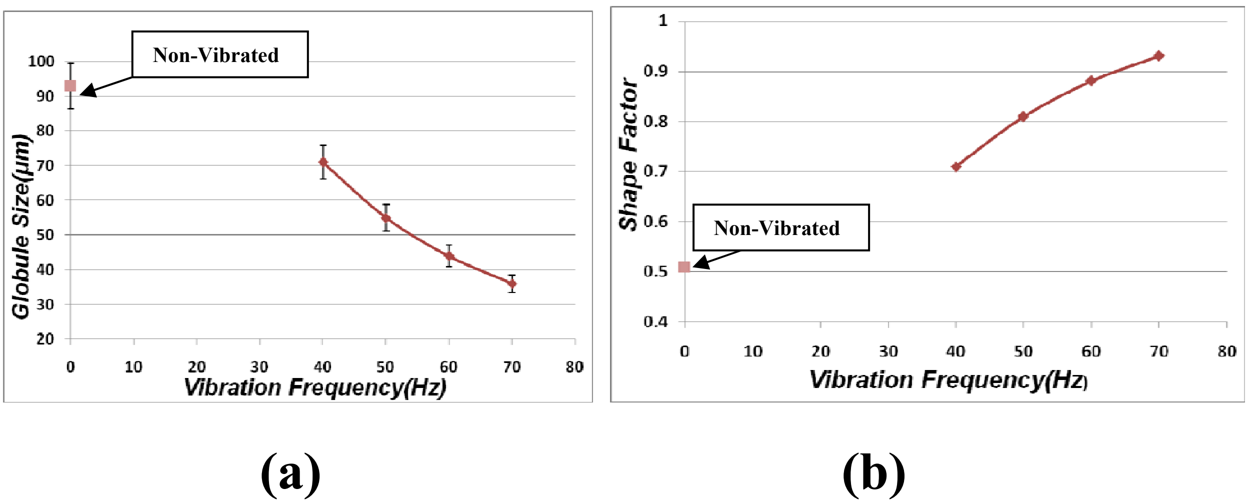

Fig. 6. The variation of (a):the effective diameter (D_e) and (b): shape factor (SF) of the globules as a function of the vibration frequency for the as-cast VCS processed samples.

In fact the main effect of vibration on the structure of solidifying metals and alloys is the suppression of columnar growth by fragmentation of the growing dendrites [12]. This grain refinement can be explained by several mechanisms such as (i) intensified flow of the liquid metal around dendrite arms; (ii) bending stresses induced on growing dendrites due to vibration induced movement of the liquid between them and (iii) re-melting of dendrite arms at the necks due to increased temperature fluctuations as a consequence strong motion of liquid. In the VCS technique, the formation and fragmentation of dendrite arms may occur near the contact surface of the cooling slope in the partially solidified flowing melt. Based on three mechanisms described above, these crystals, formed by detachment of weak dendrite arms along the cooling plate grow in the mold. In the present work, vibration of the slope results in much pronounced fragmentation of dendrite arms and intensified detachment of them from the cooling plate providing more sites for heterogeneous nucleation of new crystals. In this case, the applied shear stress is sufficient to globularize the structure. The number of the seed crystals and the extent of the shear stress applied on them are therefore affected by the vibration frequency. Therefore the increased vibration frequency increases the number of nucleated crystals and intensifies their fragmentation process resulting in decreased size of globules (Fig. 6a). Also the increased vibration frequency contributes to the increased shear stress applied on the growing crystals in the solidifying melt resulting in generation of more spherical globules (Fig. 6b).

4. Conclusions

1- A globular microstructure in aluminum A356 alloy was achieved by conventional cooling slope casting (slope angle of 45º and plate length of 400mm) only after re-melting into the semisolid state.
2- By using a newly developed technique termed Vibrating Cooling Slope (VCS), it is possible to generate globular structures in A356 alloy in the as-cast condition.
3- In the VCS process, by increasing the vibration frequency, at the fixed amplitude of 400 µm, the size of globules was reduced and their morphology became more spherical.

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