The International Journal of Advanced Manufacturing Technology (2018) 97:1617–1626
https://doi.org/10.1007/s00170-018-2063-1

ORIGINAL ARTICLE

Effect of tilted plate vibration on solidification and microstructural and mechanical properties of semisolid cast and heat-treated A356 Al alloy

N. K. Kund [1]

Received: 1 February 2017 / Accepted: 24 April 2018 / Published online: 30 April 2018

Abstract

A356 Al alloy melt solidified partially while flowing down a bottom cooled tilted plate. Columnar dendrites were formed on the plate wall. Because of forced convection, the dendrites were sheared off into equiaxed/fragmented grains and washed away by producing semisolid slurry at plate exit. Plate vibration enabled necessary shear for generating slurry which got solidified in metal mold to produce semisolid-cast billets of desired microstructure. Semisolid-cast billets were also heat treated to improve surface quality. The present investigation illustrates effect of plate vibration on solidification and microstructural and mechanical properties of semisolid-cast and heat-treated billets produced using tilted plate. This study involves five different plate vibrations (0, 15, 30, 40, and 50 Hz). Plate vibration of 30 Hz gave the finest and globular microstructure with superior mechanical properties. Because, little lower plate vibration slowed down dendrite fragmentation and grain refinement owing to inadequate shearing causing increase in grain size and decrease in shape factor, primary α-phase fraction, and grain density. Whereas, little higher plate vibration caused coarsening (which opposes grain refinement) due to coalescence/agglomeration and Ostwald ripening also resulting the same. Such variation in grain size with plate vibration caused variations in mechanical properties because of Hall–Petch effect. The results obtained are along the expected lines and in very good agreement with the results available in the literature.

Keywords A356 Al alloy · Plate vibration · Semisolid cast · Microstructure · Mechanical properties

1 Introduction

Owing to the stringent environmental regulations worldwide, particularly in the automotive sectors, the attention is intensifying more for producing eco-friendly materials with superior strength, reduced weight, higher performance efficiency, and better safety. Because of such requirements, the light weighting is not the choice but is the compulsion. Furthermore, the deployment of biotechnology, natural fuels, and hybrid/electric/fuel cell vehicles puts up a burden of additional 100- to 300-kg weight.

However, the application of usual high-strength steel, hot press, and TWB technology will never serve the purpose. As a result, for the prospect growth of automotive sectors, materials lighter than steel with superior/excellent strength are very much essential [1]. Accordingly, aluminum alloys are also being used extensively as future generation materials for making automotive parts [2]. However, the components produced with the conventional casting (where metal is directly cast at the liquid state) of aluminum alloy have inferior strength due to dendritic microstructure [3]. The present research work relates to a cutting-edge technology namely semisolid metal (SSM) processing where metal is cast at semisolid state to produce SSF components of superior mechanical and microstructural properties because of globular or thixotropic microstructure [4–6].

Application of vibrational energy is one of the methods in material processing to produce thixotropic microstructures of cast components. Based on vibration sources, there are three types of vibrational energy: mechanical, electromagnetic, and

✉ N. K. Kund
nirmalkund@gmail.com

[1] Department of Production Engineering, VSS University of Technology, Burla 768018, India

ultrasonic [5–12]. Amidst, only electromagnetic vibration is used to produce thixotropic microstructures at an industrial scale. But, high costs and ultra-sophistications are the usual drawbacks of this technology. Recently, use of ultrasonic vibrations to produce thixotropic microstructures is increased [10–12]. However, high costs and low durability of transducers are the drawbacks of this technology. Simplicity and low costs are advantages of mechanical vibration over others. Reports on use of mechanical vibration to produce thixotropic microstructures are relatively less [13–19]. Numerical studies along with the scaling analysis of solidification and macrosegregation of liquid aluminum alloy flowing on a cooling slope have also been reported in literature [20, 21]. The studies on the production of thixotropic microstructures by using tilted plates are also reported [22–25]. The vibration creates the forced convections in the melt and causes detachment of dendrite arms due to the viscous drag forces. The investigations on the vibration-induced flow exerting external forces on dendrite arms are also presented [26]. The studies on the coarsening resulting from the coalescence and agglomeration of neighboring dendrite arms and Ostwald ripening are reported as well [27]. Because of the increasing diffusion flux from high to low roundness interfaces, the smaller solid particles are dissolved in the liquid due to Ostwald ripening [9, 28]. The particle density decreases because of coarsening causing the agglomeration of these solid particles. The coarsening is controlled by the diffusion. Hence, creating the forced convection by vibration accelerates diffusion in the liquid and causes coarsening. Additionally, the investigations on mechanically or ultrasonically assisted mold vibrations are also reported in the recent literature [29–34].

Most of the mechanical vibration-related studies reported in literature are limited to mold vibrations during solidification. In addition, their investigations are confined mostly to microstructure morphology except very few researches on microstructure characterization even restricted to grain size and shape factor. There is no such comprehensive experimental study pertaining to the influence of tilted plate vibration on mechanical properties of semisolid-cast and heat-treated billets produced using tilted plate. With this standpoint, the present work illustrates the experimental studies on the effects of tilted plate vibration on solid fraction of semisolid slurry collected at the plate exit along with grain size, shape factor, primary α-phase fraction, and grain density in addition to ultimate tensile strength, yield strength, hardness, and elongation of semisolid-cast and heat-treated billets of A356 Al alloy (meant for producing thixotropic microstructure with superior mechanical properties). The present investigations involve isothermal holding of semisolid-cast billets so as to produce heat-treated billets with superior surface quality. Microstructures of semisolid-cast and heat-treated billets are evaluated and compared using optical microscopy and image analysis technique. Whereas, the mechanical properties of the same are determined by means of different material testing machines.

2 Experimental

The vibrating tilted plate apparatus consists of a stainless steel tilted plate fixed on a steel frame. The assembly is mounted on a steel plate which can vibrate at different frequencies by a mechanical vibrator/sieve shaker attached to the plate from underneath. The vibration source is a device equipped with a magnetic coil that generates different frequencies of mechanical vibration by varying supplied voltage ranging from 0 to 110 V relating to the AC power source/supply. Figure 1 describes a photograph of the experimental facility involving tundish, tilted plate (of 250-mm length and 60° inclination), metal mold, and water channel underneath the plate for performing the experiments. Details about the apparatus can also be seen in references [16–19]. The mechanical vibrator is turned on and A356 Al alloy melt is poured into stainless steel metal mold via vibrating tilted plate. In actual practice, only the tilted plate is vibrated vertically at different undermentioned frequencies by the mechanical vibrator attached to the tilted plate from underneath, whereas, the stainless steel metal mold remains stationary. Experiments are conducted with 0-, 15-, 30-, 40-, and 50-Hz vibration frequencies.

2.1 Materials

A356 Al alloy ingots of liquidus temperature 618 °C, solidus temperature 578 °C, and composition [19] as described in Table 1 are deployed in the current experimental study.

2.2 Melt preparation and treatment

Nerly 20 kg of A356 Al alloy ingot is taken in a mica glazed silicon carbide crucible. Then, it is melted in a tilting electric resistance furnace at about 720 °C. The melt is kept at that temperature for almost 45 min to gain temperature uniformity and for complete dissolution of alloying elements. Then, the predetermined quantities of Al–Sr master alloy (amounting to 0.25% of the total melt weight of the alloy) as grain modifier and Ti–B tablet (amounting to 0.125% of the total melt weight of the alloy) as grain refiner are added. The melt is allowed to soak for nearly 15 min for uniform mixing of grain modifier and grain refiner. While performing the experiments, a 40–50 °C drop in temperature of melt is usually noticed (depending on the amount of melt and degree of superheat) during transfer from the heating furnace. This establishes the inevitability of maintaining such high temperature in the electric resistance furnace.

2.3 Slurry production and temperature measurements

Approximately 1.5 kg of melt is transferred from the heating furnace into a tundish for performing each experimental study. The melt temperature in the tundish is regularly measured with K-type mineral-insulated (MI) twisted-pair thermocouples made by UK based TC Ltd. The melt at a temperature of 625 °C is gently poured into the metal mold via the bottom cooled vibrating tilted plate of length 250 mm and inclination 60°. The temperature of A356 Al alloy semisolid slurry collected at the plate exit is also measured time and again.

2.4 Semisolid billet casting and induction reheating

The semisolid-cast billets of length 250 mm and diameter 60 mm are obtained by quenching A356 Al alloy semisolid slurry in the said metal mold. For improving the microstructures, some of the semisolid-cast billets are reheated in an induction furnace as well, up to slightly above solidus temperature. And also, the present induction reheating involves isothermal holding of semisolid-cast billets at a temperature of 580 ± 2 °C to get the desired heat-treated billets.

The induction reheating is performed by applying a 25-kW power with a three-step heating cycle. In order to achieve the target of reheated billets of globular microstructure morphology with the uniform distribution of eutectic throughout, the temperature is appropriately selected and the heating cycle is tuned and trials are conducted with the semisolid-cast billets produced by using the vibrating cooling slope. The temperature of about 580 ± 2 °C is attained during the induction reheating by following the steps

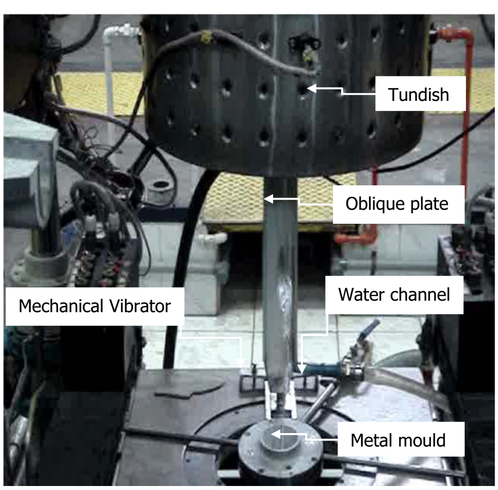


Fig. 1 Photograph of the experimental facility

Table 1 Composition of A356 alloy (as presented in [19])

Alloy element	Si	Mg	Fe	Mn	Cu	Ti	Al
Percentage by weight	7.32	0.31	0.086	Max 0.1	Max 0.2	0.157	Balance

mentioned in Table 2, which describes in detail about the heating cycle with power of 25 kW.

2.5 Specimen preparation

Small sections are cut from both semisolid-cast and heat-treated billets to obtain 15-mm-thick disks. The emery papers of different grades are used to polish all the disk-shaped samples. Then, SiC powder polishing followed by diamond paste polishing of the stated samples is also done. Thereafter, all the polished specimens prepared by the stated procedure are etched at the ambient temperature using Keller's reagent (1 ml HF, 1.5 ml HCl, 2.5 ml HNO_3, and 100 ml H_2O) to make it ready for the metallographic analysis.

2.6 Microstructure morphology and characterization

The optical microscopy is deployed to know microstructure morphology and image analysis software is utilized to estimate and quantify the heterogeneity in microstructure. The micrograph images of samples are snapped using a Leitz optical microscope to know microstructure morphology. Sigma Scan Pro image (version. 4.0) analysis software is used for microstructure characterization and quantitative metallographic analysis (for instance, to measure the perimeter and area of primary α-phase particles). The microstructure characterizations of the snapped images are done to calculate the following parameters:

a) Fraction of primary α-phase (%): It is calculated according to the area ratio of primary α-phase and eutectic Si phase.
b) Grain size: It is measured by using the intercept method.
c) Shape factor: It is the degree or extent of globularity of the primary α-phase. It is calculated by using the formula $S = 4\pi A/P^2$, where "A" and "P" are the area and the perimeter of the primary α-phase, respectively. For an ideal circle, the value is 1, and for a dendrite, the formula gives a value approaching to zero. For a rosetted structure, subjected to the degree or extent of irregularity, it gives a value between 0 and 1.
d) Particle density: It is otherwise called as grain density. It is the number of primary α-phase particles per unit area. The bigger is this number, the superior is the degree or extent of dendrite multiplication and breakdown.

Table 2 Three-step heating cycle

Step no.	Cycle	Power maintained (kW)	Time (min)	Temperature (°C)
1	Heating	25	6	350
2	Stabilizing	6.5	1	350 ± 5
3	Heating	25	8	575
4	Stabilizing	6.5	2	575 ± 2
5	Heating	25	1	580
6	Stabilizing	6.5	2	580 ± 2

2.7 Mechanical properties

The tensile specimens were machined from the semisolid-cast and heat-treated billets. The tensile testing of the said tensile specimens were done using a material testing machine. For the smooth bar tensile tests at room temperature with tensile testing machine, the round tensile test specimens (as machined from the semisolid-cast and heat-treated billets) of 20-mm-gauge length and 4-mm diameter were used. In addition, the hardness test sections were also prepared from the stated semisolid-cast and heat-treated billets. The machined, grounded, and polished specimens of semisolid-cast and heat-treated billets (as prepared for the microstructure observations) with 60-mm diameter and 15-mm thickness were used for the hardness measurements. The Vickers hardness was measured across the stated specimens with an automatic digital micro-hardness tester using a diamond indenter of 1.96-N indenting load and 20 s of dwell time. In this way, the tensile and hardness tests were carried out to investigate the ultimate tensile strength, yield strength, percentage of elongation, and hardness of the semisolid-cast and heat-treated billets of A356 Al alloy.

3 Results and discussion

Experiments are performed at five different plate vibration frequencies (0, 15, 30, 40, and 50 Hz) for investigating the influence of plate vibration on solidification and microstructure of semisolid-cast and heat-treated billets. As higher tilted plate vibration frequency accelerates the melt flow and involves less residence time (or solidification time) of the melt flowing down on the tilted plate, the semisolid slurry temperature at the plate exit increases with the plate vibration frequency. Ultimately, it results in lower solid fraction at higher plate vibration frequency. Table 3 summarizes the temperature and solid fraction data of A356 Al alloy semisolid slurry collected at the plate exit at five different plate vibration frequencies. Additionally, Fig. 2 illustrates a plot representing the variation of solid fraction of semisolid slurry collected at the tilted plate exit with the plate vibration frequency. The solid fraction of semisolid slurry with the tilted plate vibration (at moderate frequency of 30 Hz) is found to be 17 ± 1.5% whereas that of without the tilted plate vibration (corresponding to the melt pouring temperature of 625 °C, tilted plate length of 250 mm, and the plate inclination of 60°) is reported as 24 ± 1.5% in the literature [18–21]. The results are also along expected lines and agree very well with the reports depicted in the literature [25–30]. However, the direct comparison with the results of other researchers is not possible due to non-availability of such works (pertaining to the vibration of tilted plate on solidification for preparing desired quality of semisolid slurry) in the literature.

3.1 Microstructure morphology of semisolid-cast billets

Five different semisolid-cast billets are obtained at five different tilted plate vibration frequencies. Samples are made to take micrographs for quantitative and metallographic analysis. Figure 3 demonstrates the variations in microstructural morphology of the semisolid-cast billets produced at different plate vibration frequencies.

Table 3 Temperature and solid fraction data of A356 Al alloy semisolid slurry collected at the plate exit at five different plate vibration frequencies

Vibration frequency (Hz)	T_{exit} (°C)	Solid fraction from Scheil equation (%)
0	607	24
15	609	20
30	611	17
40	613	12
50	615	8

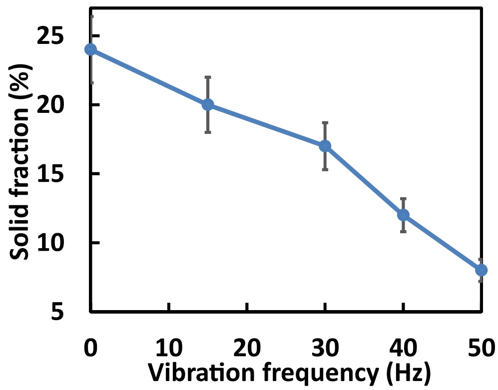


Fig. 2 Solid fraction of A356 alloy semisolid slurry versus tilted plate vibration frequency

3.2 Microstructure characterization of semisolid-cast billets

Figure 4 illustrates the microstructural characteristics obtained from quantitative and metallographic analysis of micrographs. It is observed that the grain size decreases with increase in tilted plate vibration frequency up to 30 Hz. And, the shape factor, primary α-phase fraction, and grain density increase with the same. However, with the further increase in tilted plate vibration frequency, the grain size increases, whereas, shape factor, primary α-phase fraction, and grain density decrease. The finest and globular microstructure is obtained at 30-Hz vibration with average grain size of 30 μm, shape factor of 0.85, primary α-phase fraction of 0.9, and grain density of 350.

The vibration affects the final microstructure in two ways: generating periodic tension–pressure and forced convection [4, 5]. Both of them influence the nucleation and growth behavior. The vibration creates waves in the melt by generating periodic tension–pressure forces. In the half cycle of tension, the nucleation of cavities occurs. The surface temperature of growing cavities decreases with the nucleation of fresh solid particles. In the adverse situation of cavities growth or during propagation of waves in the half cycle of pressure, the cavities collapse, thus producing shock waves causing high tension–pressure forces and nucleation in the melt. Campbell [5] observed that the cavitation takes place at very high frequency like in ultrasonic vibrations. Therefore, in the present research, the cavitation is not the cause of observed grain variation.

Conversely, the vibration also causes the forced convections in the melt. The vibration-induced flow exerts external forces on dendrite arms [20]. These viscous drag forces cause dendrite arm detachment. The detached arms encounter with the adjacent arms causing more detachment. The detached arms mix with the liquid and become new sources of nucleation [2–12]. The mechanisms of dendrites detachment and grain refinement by forced convection are bending of dendrite arms and detachment, shearing of dendrite arms and

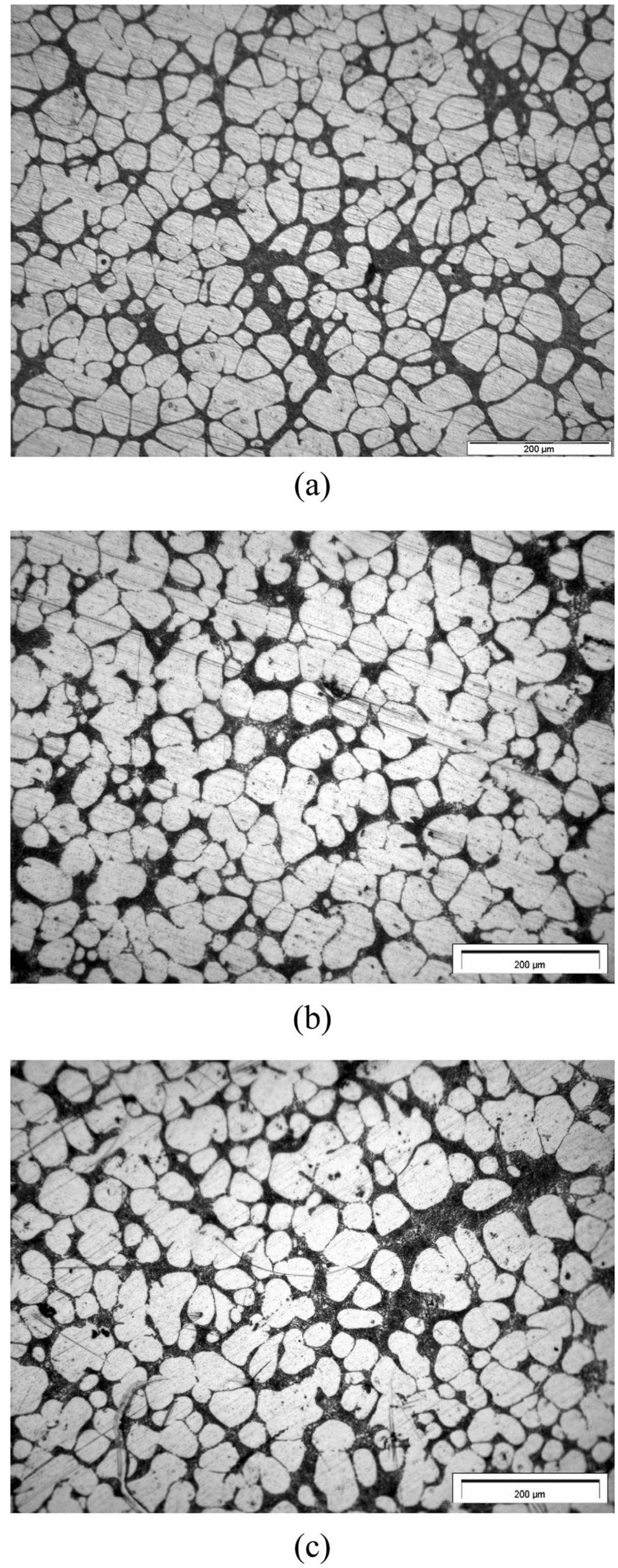


Fig. 3 Microstructures of A356 Al alloy semisolid-cast billets at vibration frequencies 0 Hz (**a**), 30 Hz (**b**), and 50 Hz (**c**)

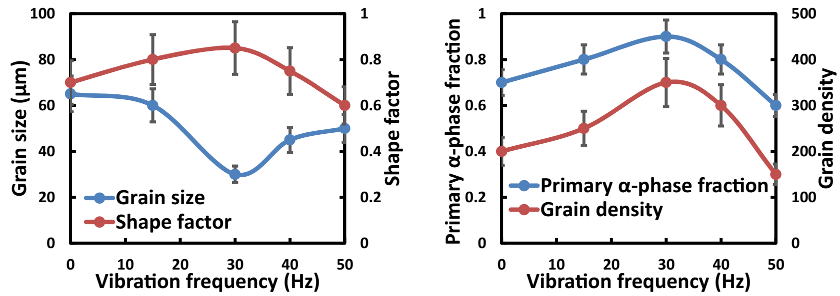


Fig. 4 Microstructure characterization of A356 Al alloy semisolid-cast billets grain size/shape factor (**a**) and α-phase fraction/grain density (count/sq. mm) (**b**)

detachment and partial remelting in root of dendrite arms, bending and recrystallization in root of dendrite arms and detachment and showering of dendrites [4–9]. The intensity of flow around the dendrites increase with the vibration frequency. Thus, the viscous drag forces on dendrites increase by causing more dendrites fragmentations. Hence, the nucleation rate increases and the further grain refinement occurs. The periodic bending of the dendrites continue with the vibration. Consequently, the number of fragmented dendrites increase by causing more grain refinement for vibration frequency up to 30 Hz (Fig. 4).

The forced convection has also a coarsening effect. The coarsening opposes grain refinement (Fig. 4), for 30–50 Hz of tilted plate vibration frequency. The decreasing surface energy is the driving force for coarsening [7–9]. The coarsening results from the coalescence and agglomeration of neighboring dendrite arms [21] and Ostwald ripening. In Ostwald ripening, the smaller solid particles are dissolved in the liquid because of the increasing diffusion flux from high to low roundness interfaces [9, 22]. The coarsening occurs by agglomeration of these solid particles causing the decrease in particle density. The diffusion controls the coarsening. Thus, creating the forced convection by tilted plate vibration accelerates diffusion in the liquid and causes coarsening.

The grain size, shape factor, primary α-phase fraction, and grain density of semisolid-cast billets with the tilted plate vibration (at moderate frequency of 30 Hz) are observed to be 30, 0.85, 0.9, and 350 μm, respectively. Whereas those of without the tilted plate vibration (corresponding to the melt pouring temperature of 625 °C, tilted plate length of 250 mm, and the plate inclination of 60°) are 65, 0.7, 0.7, and 200 μm, respectively, as described in the literature [18, 19]. And also, the results are along expected lines and in very good agreement with the reports illustrated in the literature [25–30]. But, the direct comparison with other researchers' results is not possible due to unavailability of the stated works (involving the vibration of tilted plate on microstructural properties of semisolid-cast billets) in the literature. It shows that the tilted plate vibration certainly affects the final microstructure which ultimately influences the grain size, shape factor, fraction of α-phase, and grain density.

3.3 Microstructure morphology of heat-treated billets

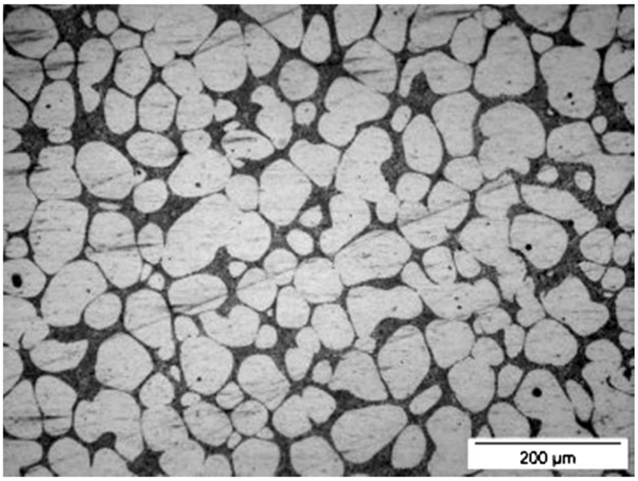
To improve the surface quality, semisolid-cast billets are heat treated up to slightly above the solidus temperature of 580 °C. The samples are made from the reheated billets. The micrographs are taken for quantitative and metallographic analysis.

Figure 5 illustrates the representative microstructures of the reheated billets so obtained. More or less uniform and globular microstructure is noticed from each reheated billet. It is due to the temperature uniformity in billets during induction reheating for about 20 min. But, the trends of variations with the tilted plate vibration frequency remain the same. The primary α-phase particles are observed to be relatively bigger.

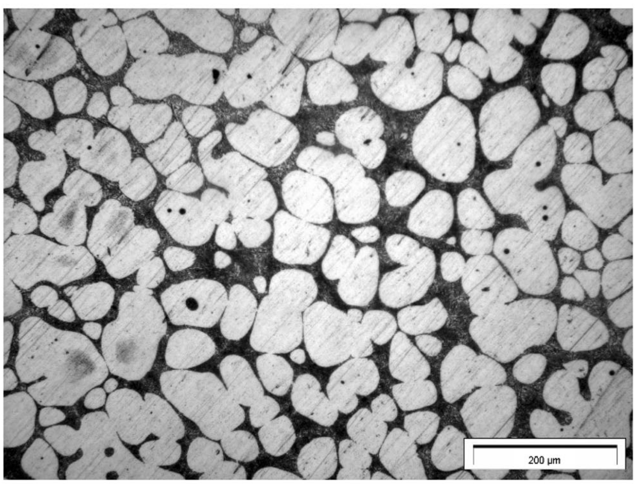
3.4 Microstructure characterization of heat-treated billets

The observations from the measurement of grain sizes, shape factors, eutectic fractions, and grain densities of semisolid-cast and reheated billets are demonstrated in Fig. 6. The grain size, shape factor, primary α-phase fraction, and grain density are observed to be more or less uniform across each reheated billet. Additionally, the trends of variations in the grain size, shape factor, primary α-phase fraction, and grain density with the tilted plate vibration frequency are the same for both the stated billets. Furthermore, it is noticed that the grain size, shape factor, and primary α-phase fraction increase with the heat treatment, while, the grain density decreases with the same. It is because of the particle coalescence during the isothermal holding. The liquid entrapment in primary α-phase is also noticed in few cases.

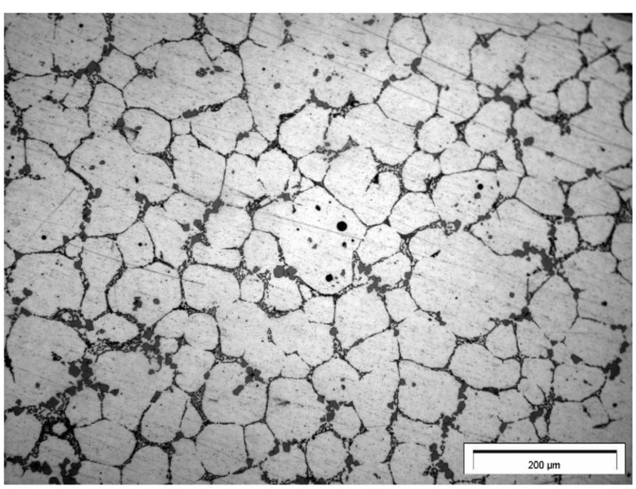
Because of the heat treatment of the semisolid-cast billets, the average grain size increases from 65 to 90 μm at 0-Hz vibration frequency, and 50 to 70 μm at 50-Hz vibration frequency through 30 to 55 μm at 30-Hz vibration frequency (Fig. 6a). Correspondingly,



(a)



(b)



(c)

Fig. 5 Microstructures of A356 Al alloy heat-treated billets at vibration frequencies 0 Hz (**a**), 30 Hz (**b**), and 50 Hz (**c**)

the shape factor increases from 0.7 to 0.8 at 0-Hz vibration frequency, and 0.6 to 0.7 at 50-Hz vibration frequency through 0.85 to 0.9 at 30-Hz vibration frequency (Fig. 6b). And also, the primary α-phase fraction increases from 0.7 to 0.8 at 0-Hz vibration frequency, and 0.6 to 0.77 at 50-Hz vibration frequency through 0.9 to 0.93 at 30-Hz vibration frequency (Fig. 6c). Similarly, the grain or particle density decreases from 200 to 145 at 0-Hz vibration frequency, and 150 to 105 at 50-Hz vibration frequency through 350 to 200 at 30-Hz vibration frequency (Fig. 6d).

The grain size, shape factor, primary α-phase fraction, and grain density of heat-treated billets with the tilted plate vibration (at moderate frequency of 30 Hz) are observed to be 55, 0.9, 0.93, and 200 μm, respectively. Whereas those of without the tilted plate vibration (corresponding to the melt pouring temperature of 625 °C, tilted plate length of 250 mm, and the plate inclination of 60°) are 90, 0.8, 0.8, and 145 μm, respectively, as reported in the literature [18, 19]. The results are also along expected lines and agree very well with the reports described in the literature [25–30]. Despite that, the direct comparison with the results of other researchers is not possible due to non-availability of such kind of works (relating to the vibration of cooling slope on microstructural properties of heat-treated billets) in the literature. This shows that the induction reheating definitely influences the final microstructure. Ultimately, it affects the grain size, shape factor, fraction of α-phase, and grain density.

3.5 Mechanical properties of semisolid-cast billets

Figure 7 illustrates the mechanical properties of semisolid-cast billets of A356 Al alloy obtained at different tilted plate vibration frequencies. It is observed that the ultimate tensile strength, yield strength, percentage of elongation, and hardness increase with the tilted plate vibration frequency up to 30 Hz. However, with the further increase in tilted plate vibration frequency, the stated mechanical properties decrease. The superior mechanical properties are obtained at 30-Hz vibration. And, the ultimate tensile strength, yield strength, percentage of elongation, and hardness of semisolid-cast billets with the tilted plate vibration (at moderate frequency of 30 Hz) are observed to be 296 MPa, 231 MPa, 13%, and 110 HV, respectively. Whereas those of without the tilted plate vibration (corresponding to the melt pouring temperature of 625 °C, tilted plate length of 250 mm, and plate inclination of 60°) are 251 MPa, 194 MPa, 8%, and 82 HV, respectively, as demonstrated in the literature [18, 19]. The results are also along expected lines of reports available in the literature [25–30]. Nevertheless, the direct comparison with the published results of other researchers is impossible due to unavailability of the said works (concerning the vibration of tilted plate on mechanical properties of semisolid-cast billets) in the literature.

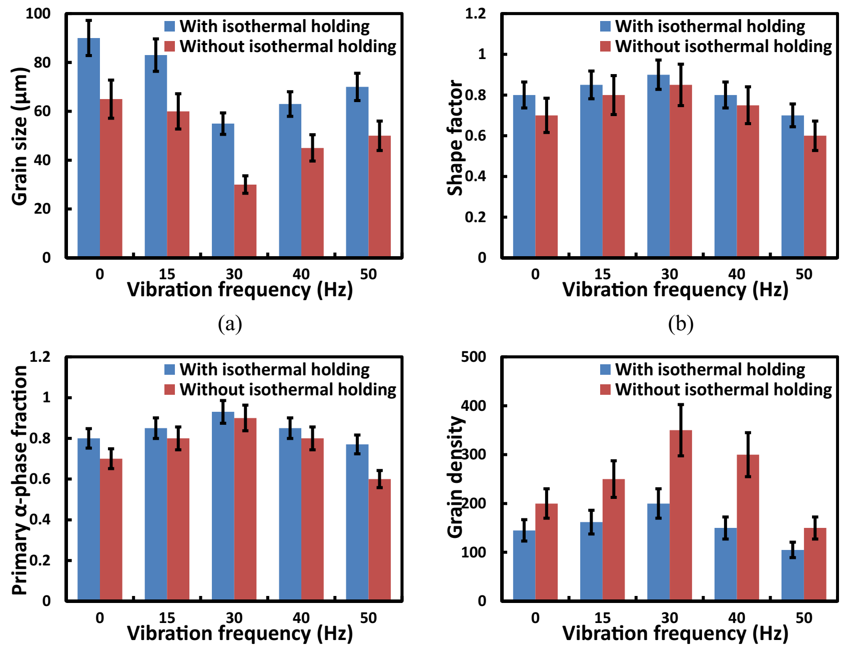


Fig. 6 Microstructure characterization of A356 Al alloy heat-treated billets grain size (**a**), shape factor (**b**), α-phase fraction (**c**), and grain density (count/sq. mm) (**d**)

Such variations in strength, hardness, and elongation can be due to two main reasons: one is porosity and the other one is microstructural refinement together with homogeneity [9]. In general, the porosity decreases strength, hardness, and ductility; the last one is particularly noteworthy. However, the porosity has got a lesser effect comparable to the microstructural refinement on the mechanical properties of semisolid-cast billets produced through the tilted plate route. The effect of microstructural refinement on mechanical properties can be well understood from the concerned Hall–Petch-type equations [9]. It is observed from the stated equations that strength, hardness, and ductility increase with decrease in grain size and vice versa. This can be owing to grain boundary strengthening or Hall–Petch strengthening. Specifically, the higher strength may be attributed to the smaller grain size; whereas, the higher ductility may be attributed to the higher shape factor together with the homogeneity in grain morphology.

3.6 Mechanical properties of heat-treated billets

The observations from the measurement of the ultimate tensile strength, yield strength, percentage of elongation, and hardness of semisolid-cast and reheated billets are demonstrated in Fig. 8. It is noticed that the said mechanical properties improve with the heat treatment. In other words, the reheated billets have superior strength, hardness, and ductility as compared to that of the semisolid-cast billets. It may be due to the reduced or even eliminated porosity and the improved dissolution of the constituent particles (i.e., increased concentration of elements dissolved in the matrix) along with the increased chemical homogeneity because of particle coalescence during the isothermal holding. In addition, the stated mechanical properties are observed to be more or less uniform across each reheated billet. However, the trends of variations in the said mechanical properties with the tilted plate vibration frequency are the same for both the stated billets.

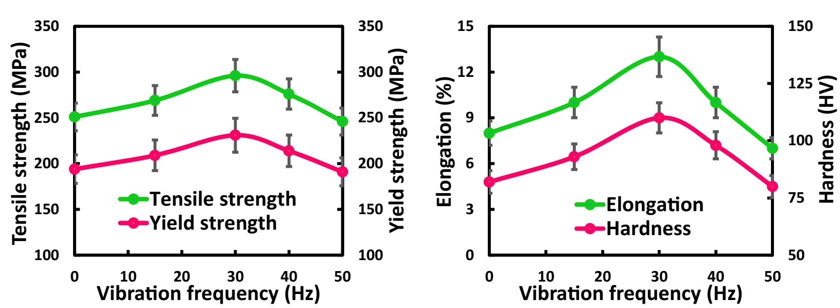


Fig. 7 Mechanical properties of A356 Al alloy semisolid-cast billets tensile strength/yield strength (**a**) and elongation/hardness (**b**)

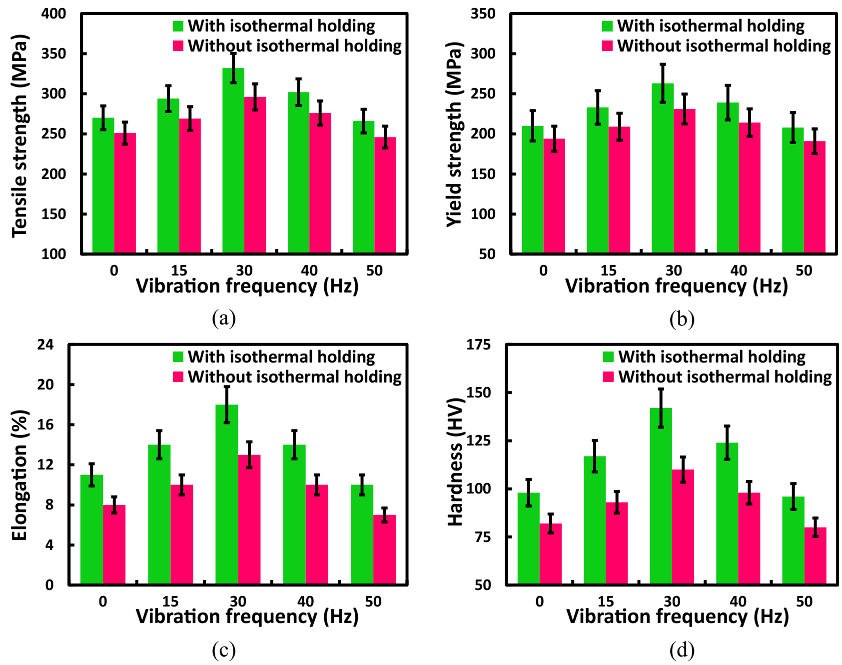


Fig. 8 Mechanical properties of A356 Al alloy heat-treated billets tensile strength (**a**), yield strength (**b**), elongation (**c**), and hardness (**d**)

Because of the heat treatment of the semisolid-cast billets, the average tensile strength increases from 251 to 270 MPa at 0-Hz vibration frequency, and 246 to 266 MPa at 50-Hz vibration frequency through 296 to 332 MPa at 30-Hz vibration frequency (Fig. 8a). Correspondingly, the average yield strength increases from 194 to 210 MPa at 0-Hz vibration frequency, and 191 to 208 MPa at 50-Hz vibration frequency through 231 to 263 MPa at 30-Hz vibration frequency (Fig. 8b). And also, the elongation increases from 8 to 11% at 0-Hz vibration frequency, and 7 to 10% at 50-Hz vibration frequency through 13 to 18% at 30-Hz vibration frequency (Fig. 8c). Similarly, the average value of hardness increases from 82 to 98 HV at 0-Hz vibration frequency, and 80 to 96 HV at 50-Hz vibration frequency through 110 to 142 HV at 30-Hz vibration frequency (Fig. 8d).

The ultimate tensile strength, yield strength, percentage of elongation, and hardness of heat-treated billets with the tilted plate vibration (at moderate frequency of 30 Hz) are observed to be 332 MPa, 263 MPa, 18%, and 142 HV, respectively. Whereas those of without the tilted plate vibration (corresponding to the melt pouring temperature of 625 °C, tilted plate length of 250 mm, and plate inclination of 60°) are 270 MPa, 210 MPa, 11%, and 98 HV, respectively, as reported in the literature [18, 19]. The results are also along expected lines of reports demonstrated in the literature [25–30]. Nonetheless, the direct comparison with other researchers' results is not possible due to non-availability of such kind of works (pertaining to the vibration of tilted plate on mechanical properties of heat-treated billets) in the literature.

4 Conclusions

For semisolid-cast billets, the grain size decreased with increase in tilted plate vibration frequency up to 30 Hz. Correspondingly, the shape factor, primary α-phase fraction, and grain density increased with the same. However, with the further increase in tilted plate vibration frequency, the grain size increased, whereas, the shape factor, primary α-phase fraction, and grain density decreased. The finest and globular microstructure was obtained at 30-Hz vibration frequency with the average grain size of 30 μm, shape factor of 0.85, primary α-phase fraction of 0.9, and grain density of 350. As, little lower vibration frequency decelerated dendrite fragmentation and grain refinement due to insufficient shearing resulting in increase in grain size and decrease in shape factor, primary α-phase fraction, and grain density. While, little higher plate vibration caused coarsening owing to coalescence/agglomeration and Ostwald ripening resulting the same as well. In addition, strength, hardness, and elongation increased with the tilted plate vibration frequency up to 30 Hz. However, with the further increase in tilted plate vibration frequency, the stated mechanical properties decreased. The superior mechanical properties were obtained at 30-Hz vibration with the average tensile strength of 296 MPa, yield strength of 231 MPa, elongation of 13%, and hardness of 110 HV. Such variations in strength, hardness, and elongation could be mainly due to microstructural grain refinement involving grain boundary strengthening or Hall–Petch strengthening. Precisely, the higher strength may be due to the smaller grain size, whereas, the higher ductility may be owing to the higher shape factor alongside the homogeneity in grain morphology. Furthermore, it was observed that the grain size, shape factor, and primary α-phase fraction increased with the heat treatment, whereas, the grain density decreases with the same. It may be due to particle coalescence which also caused liquid entrapment in primary α-phase as observed in few cases. It was noticed that the said mechanical properties also improved with the heat treatment due to the reduced/eliminated porosity, improved dissolution of the constituent particles in the matrix and the increased chemical homogeneity. The trends of variations in microstructural/mechanical properties with plate vibration frequency remained the same for both semisolid-cast and heat-treated billets. The results were also along expected lines and agree very well with the reports described in the literature. However, the direct comparison with the results of other researchers was not possible due to unavailability of such kind of works (pertaining to the vibration of cooling slope on solidification and microstructural and mechanical properties of semisolid-cast and heat-treated billets) in the literature.

Funding information The financial support received from Ministry of Mines, TIFAC, and DST is gratefully acknowledged.

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

References

1. Form GW, Wallace JF (1960) Typical microstructure of cast metals. Trans AFS 68:145–156
2. Campbell J (1981) Solidification technology in the foundry and casthouse. Metals Soc 61–64
3. Motegi T, Ohno A (1987) Solidification processing. Institute of Metals 176–179
4. Flemings MC (1991) Behaviour of metal alloys in the semi-solid state. Metall Trans A 22:957–981
5. Kirkwood DH (1994) Semi-solid metal processing. Int Mater Rev 39:173–189
6. Fan Z (2002) Semisolid metal processing. Int Mater Rev 47:49–85
7. Fisher TP (1973) Effects of vibrational energy on the solidification of aluminium alloy. British Foundryman 66:71–84
8. Abd-El-Azim AN (1981) Effect of low frequency mechanical vibration on the structure of Al-Si eutectic alloys. Mater Sci Forum 7:118–120
9. Campbell J (1981) Effects of vibration during solidification. Int Mater Rev 2:71–106
10. Abramov VO, Abramov OV, Straumal BB, Gust W (1997) Hypereutectic Al–Si based alloys with a thixotropic microstructure produced by ultrasonic treatment. Mater Design 18:323–326
11. Eskin GI (2001) Broad prospects for commercial application of the ultrasonic (cavitation) melt treatment of light alloys. Ultrason Chem 8:319–325
12. Jian X, Xu H, Meek T, Han Q (2005) Effect of power ultrasound on solidification of aluminium A356 alloy. Mater Lett 59:190–193
13. Kocatepe K, Burdett CF (2000) Effect of low frequency vibration on macro and micro structures of LM6 alloys. J Mater Sci 35:3327–3335
14. Abu-Dheir N, Khraisheh M, Saito K, Male A (2005) Silicon morphology modification in the eutectic Al-Si alloy using mechanical mold vibration. Mater Sci Eng A 393:109–117
15. Kocatepe K (2007) Effect of low frequency vibration on porosity of LM25 and LM6 alloys. Mater Design 28:1767–1775
16. Gencalp S, Saklakoglu N (2010) Semisolid microstructure evolution during cooling slope casting under vibration of A380 aluminium alloy. Mater Manuf Process 25:943–947
17. Gencalp S, Saklakoglu N (2012) Effects of low-frequency mechanical vibration and casting temperatures on microstructure of semisolid AlSi8Cu3Fe alloy. Arab J Sci Eng 37:2255–2267
18. Jiang W, Fan Z, Liu D, Wu H (2013) Influence of gas flowrate on filling ability and internal quality of A356 aluminum alloy castings fabricated using the expendable pattern shell casting with vacuum and low pressure. Int J Adv Manuf Technol 67:2459–2468
19. Jiang W, Fan Z, Chen X, Wang B, Hebao W (2014) Combined effects of mechanical vibration and wall thickness on microstructure and mechanical properties of A356 aluminum alloy produced produced by expendable pattern shell casting. Mater Sci Eng A 619:228–237
20. Kund NK, Dutta P (2010) Numerical simulation of solidification of liquid aluminium alloy flowing on cooling slope. Trans Nonferrous Met Soc China 20:s898–s905
21. Kund NK, Dutta P (2012) Scaling analysis of solidification of liquid aluminium alloy flowing on cooling slope. Trans Indian Institute of Metals 65:587–594
22. Kund NK (2014) Influence of melt pouring temperature and plate inclination on solidification and microstructure of A356 aluminum alloy produced using oblique plate. Trans Nonferrous Met Soc China 24:3465–3476
23. Kund NK (2015) Influence of plate length and plate cooling rate on solidification and microstructure of A356 alloy produced by oblique plate. Trans Nonferrous Met Soc China 25:61–71
24. Kund NK, Dutta P (2015) Numerical study of solidification of A356 aluminum alloy flowing on an oblique plate with experimental validation. J Taiwan Inst Chem Ers 51:159–170
25. Kund NK, Dutta P (2016) Numerical study of influence of oblique plate length and cooling rate on solidification and macrosegregation of A356 aluminum alloy melt with experimental comparison. J Alloys Compd 678:343–354
26. Doherty RD (2003) Comments on mechanical deformation of dendrites by fluid flow during the solidification of undercooled melts. Scripta Mater 49:1219–1222
27. Genda G, Yuyon C, Geing A (1987) Mechanism of coarsening of dendrite during solidification. Proceedings Inglaterra 416–419
28. Wan G, Sahm PR (1990) Ostwald ripening in the isothermal rheocasting process. Acta Metall Mater 38:967–972
29. Abdul-Karem W, Green N, Al-Raheem KF (2012) Vibration-assisted filling capability in thin wall investment casting. Int J Adv Manuf Technol 61:873–887
30. Abdul-Karem W, Green N, Al-Raheem KF, Hasan AHA (2013) Effect of vibration after filling on mechanical reliability in the thin wall investment casting with fillability filling regime-part 1. Int J Adv Manuf Technol 67:2075–2082
31. Guo HM, Zhang AS, Yang XJ, Yan MM, Ding Y (2014) Microstructure formation and mechanical properties of AZ31 magnesium alloy solidified with a novel mechanical vibration technique. Metall Mater Trans A 45:438–446
32. Zhang X, Kang J, Wang S, Ma J, Huang T (2015) The effect of ultrasonic processing on solidification microstructure and heat transfer in stainless steel melt. Ultrason Sonochem 27:307–315
33. Ruirun C, Deshuang Z, Jingjie G, Tengfei M, Hongsheng D, Yanqing S, Hengzhi F (2016) A novel method for grain refinement and microstructure modification in TiAl alloy by ultrasonic vibration. Mater Sci Eng A 653:23–26
34. Jiang W, Chen X, Wang B, Fan Z, Wu H (2016) Effects of vibration frequency on microstructure, mechanical properties, and fracture behaviour of A356 aluminum alloy obtained by expendable pattern shell casting. Int J Adv Manuf Technol 83:167–175