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Induction reheating of A356.2 aluminum alloy and thixocasting as automobile component

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Abstract: The development work for producing an automobile component by thixocasting using A356.2 alloy was introduced. As the first step, the alloy was electromagnetically stirred and solidified to produce a billet with non-dendritic microstructure. The microstructure depended on several process parameters such as stirring intensity, stirring frequency, cooling rate, and melt initial superheat. Through a series of computational studies and controlled experiments, a set of process parameters were identified to produce the best microstructures. Reheating of a billet with non-dendritic microstructure to a semisolid temperature was the next step for thixo-casting of the components. The reheating process was characterized for various reheating cycles using a vertical-type reheating machine. The induction heating cycle was optimized to obtain a near-uniform temperature distribution in radial as well as axial direction of the billet, and the heating was continued until the liquid fraction reached about 50%. These parameters were determined with the help of a computational fluid dynamics (CFD) model of die filling and solidification of the semisolid alloy. The heated billets were subsequently thixo-cast into automobile components using a real-time controlled die casting machine. The results show that the castings are near net shape, free from porosity, good surface finish and have superior mechanical properties compared to those produced by conventional die casting processes using the same alloy.
Key words: aluminum alloy; thixo-casting; electromagnetic stirring; induction reheating; process parameters

1 Introduction

For the production of high performance aluminum components, various techniques have been developed recently, such as gravity die-casting, pressure die casting, squeeze casting and liquid metal forming. One of the major drawbacks of these processes, however, is the dendritic evolution of the microstructure which leads to defects and cracking. Many other difficulties of these chilled casting processes are porosity, turbulent filling of mould and shrinkage. Research for overcoming these difficulties gave rise to a new forming process, namely the semisolid manufacturing (SSM)[1], for production of commercial components of extremely high casting integrity and excellent properties. In contrast with the conventional casting processes, SSM relies on the production of slurry which has the physical state between solidus and liquidus temperature (mushy state).

FLEMINGS[1] proposed two basic variants of the SSM process. These are called “rheocasting” and “thixocasting”, as described in Fig.1. Both processes involve the usage of stirring devices during freezing to create the spheroidal non-dendritic microstructure. Among the various techniques that exist today to produce semisolid feedstock, electromagnetic stirring (EMS) is considered to be the most effective, due to its non-intrusive nature and scope for precise process control [2–4]. Rheocasting envisages preparing semisolid slurries directly beside a die-casting machine and casting the slurry into components. In a thixocasting process, the raw material is prepared in the form of billets with non-dendritic microstructure. Subsequently, this raw material is reheated to a temperature in the mushy zone and processed into the final parts.

The thixocasting technology consists of two basic

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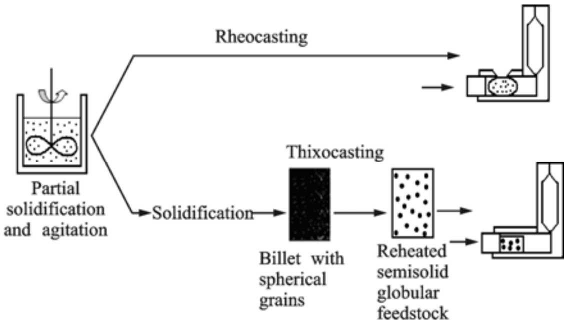

Fig.1 Classification of semisolid processes

processes: 1) Production of non-dendritic microstructure billets; 2) Processing of non-dendritic billets to make components. However, the technological adaptation from conventional casting processes to a thixocasting process is not a straight forward exercise, as there are several steps with small windows of success. Casting of non-dendritic billets using electromagnetic stirring depends on many parameters[5], such as the stirring intensity, excitation frequency and cooling rate. A minimum shear rate should be produced by the EMS so that dendrites can be detached from their roots. The position of the stirrer in the mould is also very important. All these parameters affect the overall solidification process which will determine the final microstructure.

Subsequent to the production of non-dendritic microstructure billets, the process of re-heating of the billet to the desired semisolid temperature is also a challenging task. Induction heating is generally used to reheat the billets in semisolid state[6−9], in which a major objective is to minimize non-uniformity in temperature distribution. In this context, HIRT et al[6−7] and KANG et al[9] predicted temperature distribution of aluminum alloy billets using a finite difference method where Bessel functions were used to describe the electromagnetic fields. KO et al[10] and KAWAGUCHI et al[11] predicted the temperature distribution during induction heating based on a finite element method. CHOI et al[12] calculated the temperature distribution analytically considering induction heating and compared their results with experiments. BARMAN et al[13] developed a numerical model based on finite volume method to predict temperature variation with a billet during induction heating. It is shown in Ref.[13] that in a typical induction reheating process, the heating is generally non-uniform in nature, and there must be a careful design of reheating cycle to heat the billet uniformly along its length and cross section. A near-uniform heating within a desired time is required to attain the right solid fraction range for a successful thixocasting operation. In addition, appropriate die and shot sleeve designs, along with die temperature control are critical for casting of the semisolid component. It is, therefore, not surprising that the design changes and process development for every semisolid formed components need significant R&D efforts, demanding close industry-academia tie-up.

The present paper describes the casting of an automobile component using the thixocasting route. As the first step, the alloy was electromagnetically stirred and solidified to produce a billet with non-dendritic microstructure. Through a series of computational studies and controlled experiments, a set of process parameters were identified for producing the best microstructures. Reheating of a billet with non-dendritic microstructure to a semisolid temperature was the next step for thixocasting of components. The reheating process was characterized for various reheating cycles using a vertical-type reheating machine. The induction heating cycle was optimized to obtain a near-uniform temperature distribution in radial as well as axial direction of the billet. The choice of reheat temperature and die casting parameters depended on the viscosity variation of the semisolid material with temperature. These parameters were first determined with the help of a computational fluid dynamics (CFD) model of die filling and solidification of the semisolid alloy. The viscosity variation of the slurry, used in the model, was determined experimentally using a specially made rotary viscometer for semisolid alloys [14]. The heated billets were subsequently thixo-cast into an automobile component using a real-time controlled die casting machine.

2 SSM billet manufacturing and characterization

Non-dendritic billets of A356.2 aluminum alloy were produced in the laboratory to manufacture SSM components. A metal mould was designed in such a way that there was provision for cooling the molten metal instantaneously at the desired temperature. This was done by providing some cooling channels in the metal mould, as shown in Fig.2.

The process parameters selected to produce billets with desired microstructure were determined with the help of a computational model and rigorous experiments, as described in Refs.[15−16]. Around 20 kg A356.2 aluminum alloy ingots were loaded into a resistance furnace and melted at 850 °C. Once the metal reached molten stage, the grain refiner of Ti-B was added at 0.1% of the total metal being melted, and the modifier of aluminum-strontium of 0.06 % of the total metal being melted was added to the molten metal and allowed to soak for 10 min. Then, around 1.5 kg molten metal was transferred into a crucible at about 750 °C, and when the temperature reached 620 °C, the metal was poured into the preheated metal mould kept inside the electromagnetic stirrer. The electromagnetic stirrer was operated at 350A, 50 Hz. Once the metal temperature reached 610 °C in metal mould, the water supply for the metal mould was switched on and immediately allowed to pass through the cooling channels to quench the metal in the metal mould. The static mould billets were 230 mm in length and 75 mm in diameter. The billets thus obtained were subsequently examined with respect to microstructure. A sample with as-cast microstructure is shown in Fig.3. The microstructure shows fragmented dendrites in the form of rosettes. The eutectic phase uniformly distributes and is completely modified. The as-cast microstructure is compared subsequently with that of an induction heated billet.

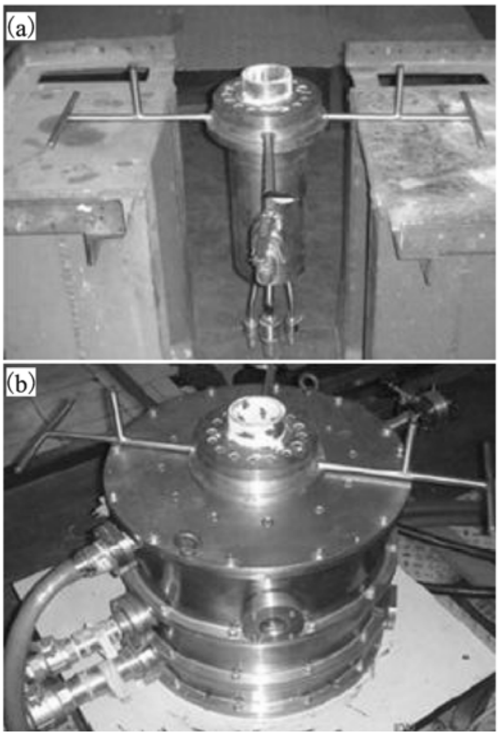

Fig.2 Photographs of metallic mould(a) and electromagnetic stirrer(b)

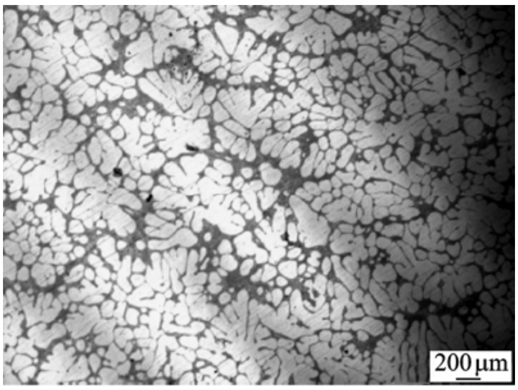

Fig.3 Microstructure of electromagnetic stirred billet at 350A, 50 Hz before induction heating

3 Induction reheating and microstructure

Semi-solid manufacturing requires heating the work piece to the semisolid state with coexisting liquid and solid phases. The technique usually requires reheating the pre-processed feed stock with a fine and non-dendritic structure up to typical liquid fraction of about 50%. So the heating process must be accurately controlled to achieve a uniform temperature distribution in the material and in turn, the liquid fraction. On the other hand, the heating process is required to be relatively rapid to obtain and maintain the globular microstructure, and also to increase productivity. Induction heating is nowadays the most commonly used method in commercial production applications, especially in semi-solid metal processing, because it is a non-contact, clean, compact and fast method and the input power can be easily controlled.

The induction heating was performed by applying 25 kW power with different heating cycles. Three different heating cycles were used: 1) single step cycle, 2) two-step cycle and 3) three-step cycle. In order to achieve the required liquid fraction of about 50%, the semisolid temperature was appropriately selected and the heating cycles were tuned and trials were conducted using the non-dendritic billets produced by EM stirring. In the trial billets, thermocouples are placed at different positions in the billet as shown in Fig.4, to record the temperature profile with elapse of time. The temperature of 580 °C to be attained during the induction heating to achieve a solid fraction of 50% is determined from the graph represented in Fig.5[17]. Tables 1–3 describe the heating cycles with power of 25 kW.

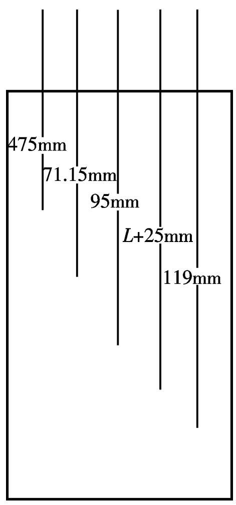

Fig.4 Location of thermocouples in billet during induction heating

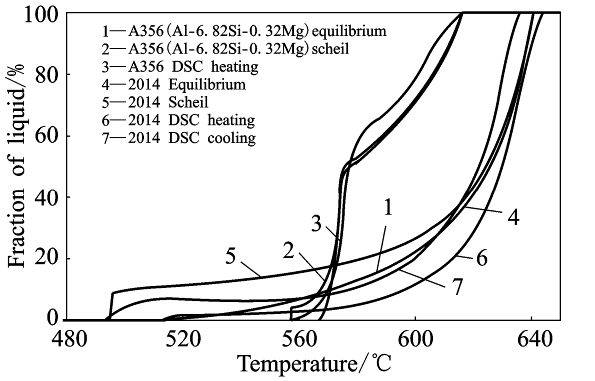

Fig.5 Curves of liquid fraction vs temperature[17]

Table 1 Single step cycle

Step No.	Cycle	Power Maintained/kW	Time/ min	Temperature/ °C
1	Heating	2.5	16	580
2	Stabilizing	6.5	3	575±5

Table 2 Two step cycle

Step No.	Cycle	Power Maintained/kW	Time/ min	Temperature/ °C
1	Heating	25	14	575
2	Stabilizing	6.5	2	575±3
3	Heating	25	1	580
4	Stabilizing	6.5	2	580±3

Table 3 Three step 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

In order to study the microstructure obtained during various induction heating cycles, the billet was quenched after different induction cycle to freeze the microstructure obtained after induction heating. During induction heating the eutectic phase melts and improves the flow ability of the material. There is some amount of melting at the surface of the α-phase during induction heating which modifies the α-phase into globular structure. Also some amount of liquid comes into the α-phase which can be observed in the microstructure. This is due to the coalescence of the neighboring α-phase.

The temperature profiles for the three heating cycles using 25 kW power are obtained, but only the profiles for the three step cycle are shown in detail (see Fig.6). The temperature variation between the core to edge/surface is observed to be 9 °C in single step, 6 °C in two step and 2 °C in three step induction heating cycle. As the semi-solid temperature window is very narrow and especially for A356 alloy it is ± 5 °C, it is critical to maintain the final temperature of the billet through-out at uniform temperature in order to maintain the solid fraction of 50% throughout.

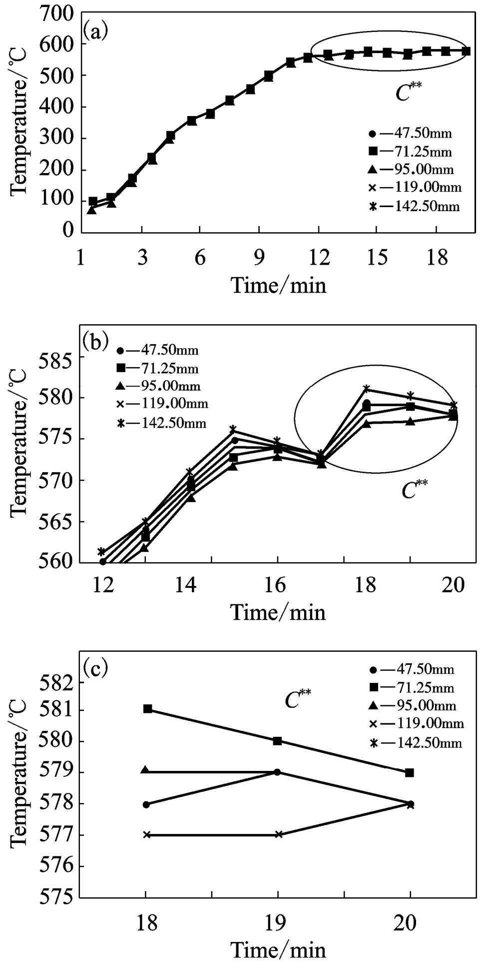

Fig.6 Temperature profiles of thermocouples located at different positions in billet during three step induction heating process at 25 kW

The microstructures obtained by three step induction heating cycle at 25 kW were examined as shown in Fig.7. The microstructures were studied along the axial and radial directions. In the radial direction the microstructure was observed at the core, middle and edge of the circular billet. Along the axial direction the microstructure was observed at top and bottom of the billet. The microstructure obtained is globular and the eutectic is uniformly distributed.

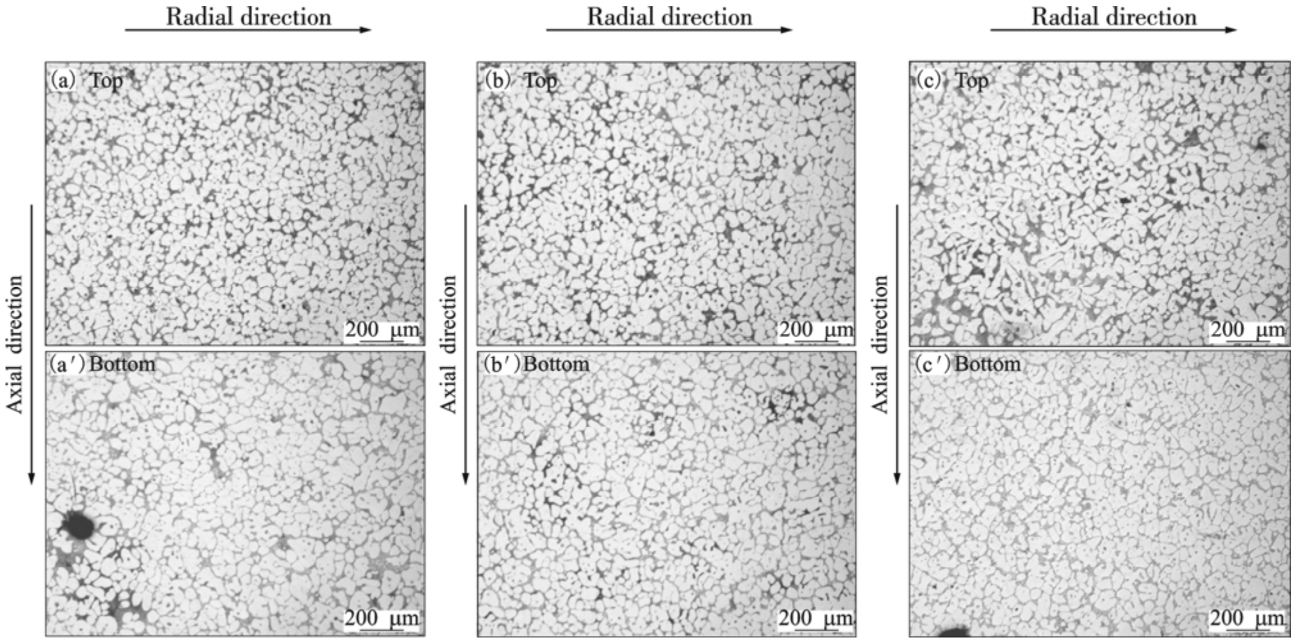

Fig.7 Microstructures of billet at different location after three step induction heating at 25 kW along axial direction and radial directions: (a),(a') *R*-core; (b), (b') Middle; (c), (c') Edge

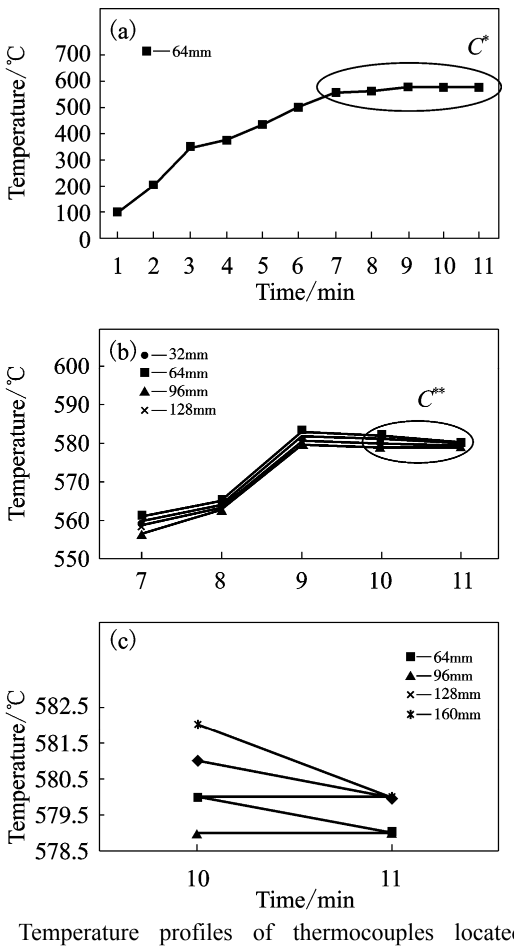

Fig.8 Temperature profiles of thermocouples located at different positions in billet during three step induction heating process at 50 kW

In order to optimize the heating time, a higher power of 50 kW was applied and the three step induction heating cycle was modified. The modified three step induction heating cycle with 50 kW power is presented in Table 4. The temperature profile of the billet during the induction cycle is represented in Fig.8. The total time for the cycle to complete was optimized to 11 min with higher power. The temperature difference achieved during the completion of the induction heating cycle between the core and the edge of the billet is 1°C. Uniform microstructure is obtained along the axial as well as radial directions of the billet as seen in Fig.9. This is achieved because the uniform temperature of (580±2)°C was maintained in the axial as well as the radial directions of the billet. The grain size obtained on the microstructure of the billet with 50 kW three step induction heating is 46 μm, which is much finer than the grain size obtained from the 25 kW three step induction heated microstructure which is 69 μm. The billet was kept for longer duration above 575 °C in 25 kW three step cycle than the 50 kW three step cycle, which has lead to the increase in grain size.

4 SSM component manufacturing by thixo-casting

Using a die for an SSM automobile component, CFD simulations were first conducted to identify the suitable range of process parameters for billet reheating and SSM die casting. For these simulations the rheological properties were experimentally obtained using a rheometer made by rheologica (Sweden). A typical simulation result using commercial CFD package Flow3D is shown in Fig.10.

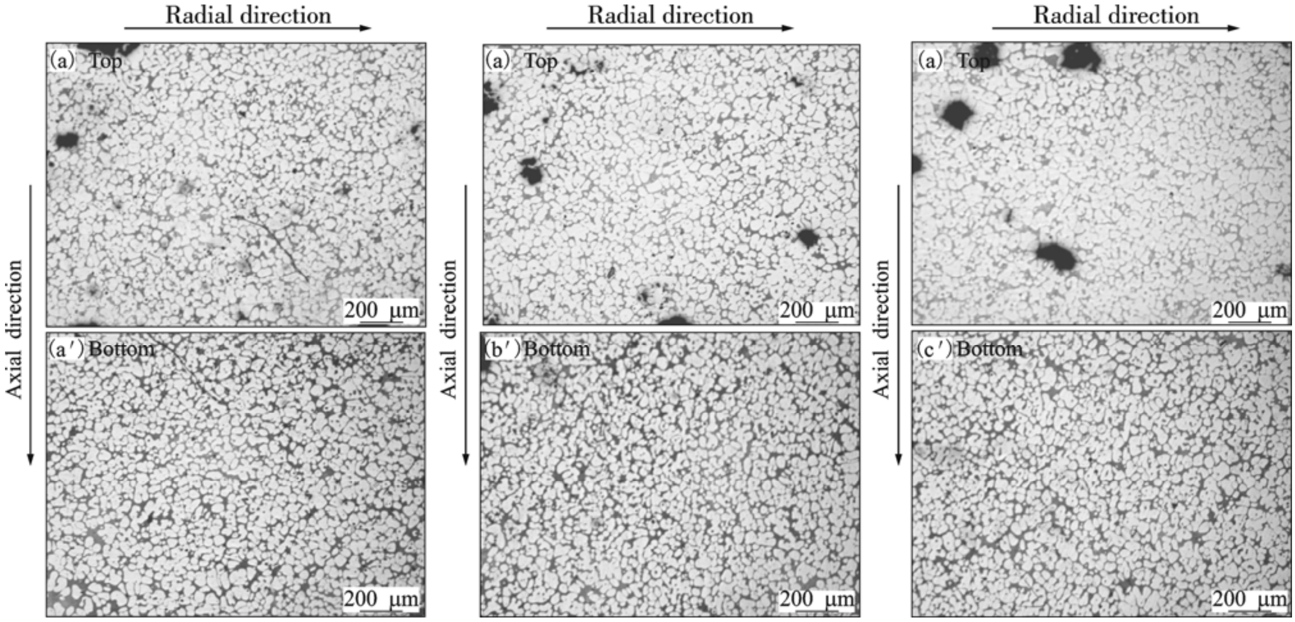

Fig.9 Microstructures of billet at different locations after three step induction heating 50 kW along axial as well as radial directions: (a),(a') *R*-core; (b), (b') Middle; (c), (c') Edge

Table 4 Three step cycle at 50 kW

Step No.	Cycle	Power Maintained/ kW	Time/ min	Temperature/ °C
1	Heating	50	3	350
2	Stabilizing	6.5	1	350±5
3	Heating	50	3	575
4	Stabilizing	6.5	1	575±2
5	Heating	50	1	580
6	Stabilizing	6.5	2	580±1

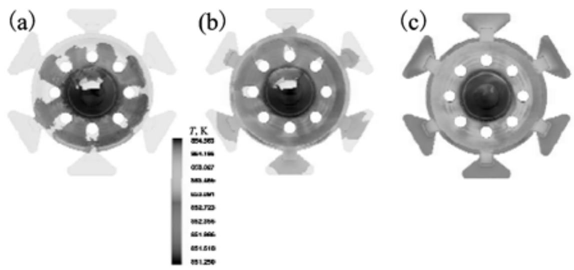

Fig.10 CFD simulation showing temperature distribution for die filling: (a) t=0.108 3 s; (b) t=0.1123 s; (c) t=0.1174 s

The induction heated billet is transferred to shot sleeve of the die casting machine to cast the wheel hub component through semisolid route. The casting was done using a 420 t Buhler die casting machine. The dies were preheated up to 200 °C. During casting the injection speed was 1.9 m/s with an intensification pressure of 1×10^8 Pa. A sample photograph of the component and its section are shown in Fig.11. It is observed that the heated billet had sufficient flowability to fill die cavity. The microstructure of the semi-solid cast component shows globular non-dendritic structure (see Fig.12).

Table 5 lists the mechanical properties of the component, along with a comparison with those from literature.

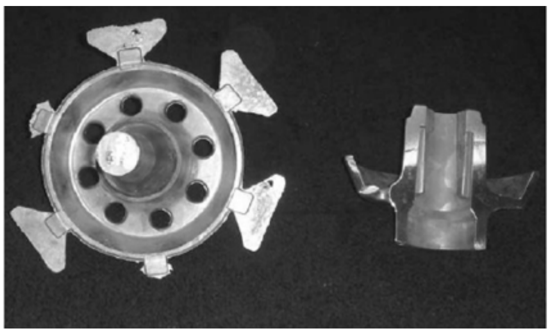

Fig.11 Sample photographs of thixocast component

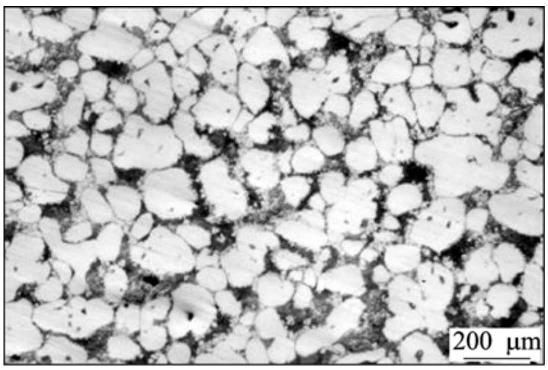

Fig.12 Microstructure of semisolid cast component

Table 5 Mechanical properties of SSM casting in literature and obtained in this work

Heat treatment	σ_b/MPa		E/%	
	In literature	In this work	In literature	In this work
As cast	200–225	209	8–15	15
T6	290–320	323	5–12	5

5 Conclusions

1) The casting development of a semisolid A356 aluminum alloy as an automobile component using the thixocasting route was introduced. It was found that the castings are near net shape, free from porosity, excellent finish and have superior mechanical properties compared to those produced by conventional die casting processes using the same alloy.

2) The selection of induction heating parameters is of utmost importance in obtaining a sound casting with desired microstructure and mechanical properties.

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