Aluminum Droplets Impinging on Copper Substrates: A Dynamic Wetting and Heat Transfer Study

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THIXOFORMING OF A357 ALUMINUM ALLOY COMPONENTS

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ABSTRACT

This paper describes experimental work at Industrial Materials Institute and Materials Technology Laboratory of CANMET on thixoforming of A357 aluminum alloy. Commercial billets of 76 mm diameter and 152 mm long are reheated under controlled conditions to obtain a globular primary phase in the microstructure. Reheating is carried out in a single coil induction unit programmed to provide the feedstock with a good consistent viscosity prior to forming. Temperature uniformity in the billet is optimized by controlling power input into the coil by means of a thermocouple strategically located in the workpiece. The semi-solid material is cast in a 600T capacity die casting machine into a box-like component weighing 1.4 kg and having a wall thickness of 5- 9 mm and a height of 90 mm. Forging is done in a 500 T capacity press to produce a disk-shaped component with a diameter of 172 mm and a weight of 1.5 Kg. In each case, parameters are selected to produce components containing no significant defects. Different sections of the components are sectioned and their microstructures are evaluated. Further, the mechanical properties of the semi-solid and liquid metal die cast components as well as forged components are determined and compared.

Key Word: SSM, Semi-Solid Casting, Semi-Solid Forging, Thixoforming, High Frequency Induction Heating, A357 Alloy, Pressure Die Casting

INTRODUCTION

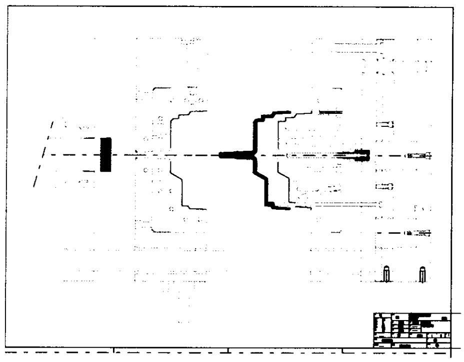
High-volume thixoformed aluminum-silicon alloy components are increasingly being manufactured for stress-bearing and structural applications in automobiles (1,2). Most are produced by reheating billets with a fine and non-dendritic structure to a fraction solid of approximately 50% and casting them in pressure die casting machines. Recently, there has been an increasing emphasis to eliminate the reheating stage altogether because of cost and other considerations such as energy savings and in-house recycling. Instead, components are cast directly from slurries prepared just prior to forming, a process commonly referred to as "slurry on demand." (3-5). Typical components now being manufactured include suspension arms, engine brackets, master brake cylinders, knuckles and fuel rails (1,3). Generally components that require superior properties not achievable by the liquid route are good candidates for thixoforming. More often than not, these components are heat-treated to further enhance their tensile properties, a procedure not recommended for conventional pressure die cast components because of blistering problems.

Work at Industrial Materials Institute over the past several years has focused on several aspects of semi-solid forming. Activities include developing techniques to reheat billets by induction efficiently, characterization of flow and solidification in the die cavity using ultrasonic sensors and optimizing conditions to produce high-integrity components in a die casting machine (6-9). At the Materials Technology Laboratory, Canmet, activities on semi-solid forming are related to the casting of thixotropic feedstock, reheating and forging of billets, and characterization of properties and microstructures (10-12). Some of these activities are part of a project to investigate semi-solid forming of lightweight components for transportation applications and are conducted jointly.

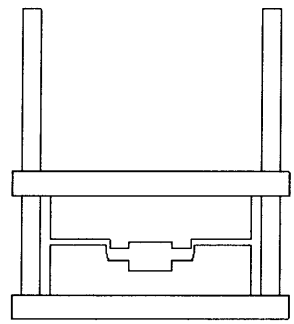
In this paper, results of experiments at the two organizations to investigate thixoforming of A357 aluminium alloy in a die casting machine and a forging press are presented.

EXPERIMENTAL

The experimental dies used for the semi-solid casting and forging trials are shown in Figure 1. The casting mould was heated by hot circulating oil while the forging mould was kept at the desirable temperature by electrical band heaters. In the casting mould, the material is injected into the cavity through a gate at the center of the billet, thereby leaving the oxide skin formed during induction heating in the biscuit. A shearing mechanism incorporated in the fixed die half removes the biscuit just prior to part ejection. The casting mould produces a 1.4 kg box-like component of 240 mm long, 138 mm wide and 90 mm deep. The wall was thickest (9 mm) near the gate and thinnest (5 mm) near the edge. The forging mould produces a disk-like component weighing 1.5 kg, with a 18 mm thinner outer section of 170 mm diameter and a 58 mm thicker inner section of 90 mm diameter.



a: Three-part casting die



b: Forging die

Figure 1: Schematics of the casting and forging dies

The A357 feedstock billets used for the experiments were purchased from Ormet. These billets of 3-inch diameter were continuously cast and electromagnetically stirred to provide a fine non-dendritic structure. Equal sections of 6 inch in length were prepared for reheating in a single-coil 20 kW induction furnace operating at 10 kHz manufactured by Norax Canada (6,10). The billets were placed centrally and vertically on a ceramic pedestal and introduced into the coil by means of a pneumatic piston. At the appropriate temperature, the pedestal was lowered to allow removal of the semi-solid material for casting or forging. In order to obtain a thixotropic material with a low consistent viscosity under shear, power into the coil was programmed for maximum input for the first 4 minutes until the temperature reached approximately 560 ° C. Current was then reduced progressively over a few steps so that a minimal power corresponding to 10 % of its original value was maintained just prior to forming. At the beginning of the trials, temperature variations in the billet were measured by means of a number of thermocouples embedded at different points.

For casting trials, the billets were transferred manually into the shot sleeve of the die casting machine when the temperature 12 mm below the center of the top face reached 585 ° C. The shot sleeve was heated to a temperature of 315 ° C by four 775 W capacity cartridge heaters installed in drilled holes in the sleeve. An intensified metal pressure greater than 500 bars (50 MPa) and a ram speed of up to 1.5 m/s during the filling phase were used. The die was maintained at a temperature of 250 -275 ° C.

A few components were also produced from liquid metal by heating the billets in a small crucible to 650 ° C. These components were evaluated for tensile properties, along with those produced from the semi-solid billets.

Semi-solid castings chosen for the T5 heat treatment were quenched in a tank of tap water at 15 ° C and artificially aged in a convection furnace for 6 hours at 170 ° C.

Forging trials were carried in a Hydropress with a 500T capacity on the upper main ram and a 150T capacity on the lower cushion ram. The temperature of the reheated billet was 575 ° C, as measured at the center of the top faced as in the case for casting. The die was maintained at a temperature of 250 – 300 ° C by two band heaters and a ram speed of 100 mm/s was used.

Samples removed for microstructure evaluations were polished to a 1μm finish and etched with 0.5% HF solution. In the cast components, sub-sized ASTM (E8-00b) tensile strip specimens were machined from flat regions at the top of box near the gate. Sub-sized ASTM round specimens were also machined from forged disks at a region near the corner between the thick and thin section. At least four specimens from each group were tested.

RESULTS AND DISCUSSION

Temperature Uniformity in Billets

The temperature distribution in the billet was first established by a series of reheating experiments aimed to measure temperatures at different points. Figure 2 shows typical temperature curves of points T1-T6 monitored by six k-type thermocouples, beginning from the time when the billet begins to melt to the time just prior to forming. It is evident that temperature discrepancies among the points increase with time, with a maximum difference of approximately 18 ° C after 375 s between the coldest and hottest points. Thereafter, the discrepancies become narrower until a temperature variation of no more than approximately 7 ° C throughout the billet is reached towards the end.

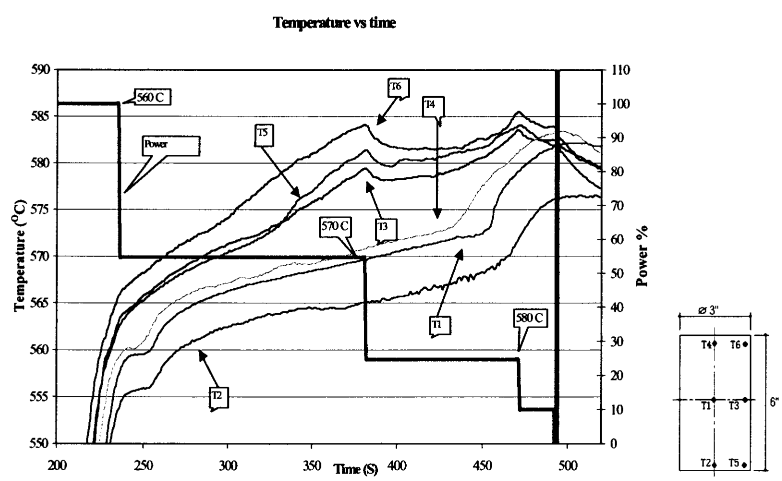


Figure 2 - Temperatures at points T1-T6 in the billet as a function of reheating time

Although the high current intensities (known commonly as the "skin" effect) on the billet surfaces account for this phenomenon in induction heating, it must also be said that the lower thermal conductivity of the alloy (115 W/m.K compared with 137 W/m.K) (13,14) in the liquid state must also be considered a contributing factor.

In terms of power input into the coil, the first reduction of approximately 50 % to prevent surface overheating occurs at around 560 ° C. This is followed by further reductions at 570 ° C and 580 ° C respectively. Power is cut off when the temperature in the top center thermocouple (T4) approaches 585 ° C. Convergence of the temperature curves after the power is cut off indicates that thermal equilibrium in the billet is being achieved through heat transfer by conduction within the material.

Casting and Forging of Billets

Billets suitable for forming were cast or forged into components shown in Figure 3. The important parameters required for producing high-integrity castings are billet temperature, metal pressure and injection speed. The billet temperature should be kept within the range of 580 - 590 ° C through the entire cross-section to ensure good consistent viscosity and flow in the mould cavity under pressure. As the material loses heat when it enters the cavity and its viscosity increases, higher metal pressure is needed to fill the mould completely. For a casting with a configuration as complex as the box, best results were obtained when an intensified metal pressure of 1200 bars (120 MPa) or higher was applied. To properly fill the mould and minimize air-entrapment in the material as much as possible, a ram speed of 1m/s was found to

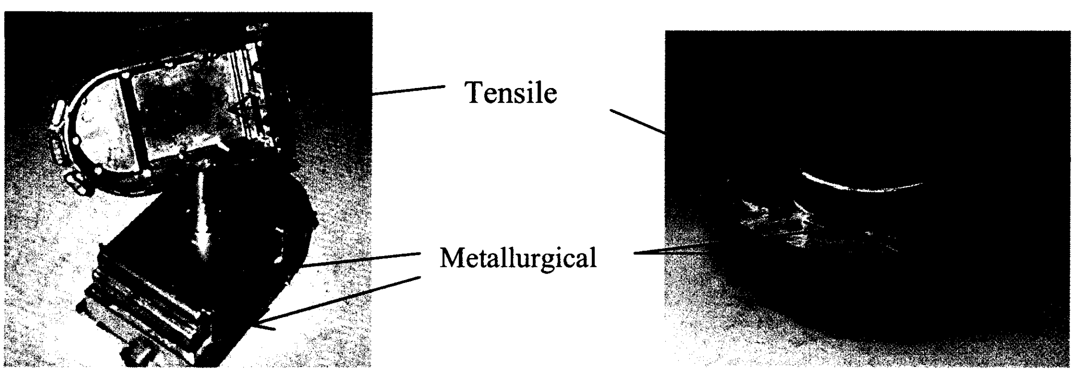


Figure 3 - External and internal views of the box castings on the left and the forged disk on the right. Locations of specimens for tensile testing and metallurgical evaluations are indicated.

be suitable, corresponding to a gate velocity of 10 m/s, which is much lower than what is commonly used in liquid pressure die casting of aluminum alloys (30-40 m/s). Heat loss by conduction to the steel in contact with the alloy should be minimized by keeping the sleeve and die temperature in the range of 250- 325 ° C.

For forging, experimental trials showed that best results were obtained when the billet temperature and die temperature was 570-580 ° C and 275 - 300 ° C respectively. Under a load of 30-50T, a ram speed of 100 mm/s was most suitable.

Microstructure

The microstructure of the as-received A357 rheocast bar shows the presence of bigger rosette-like primary alpha particles (100 μm) and finer equiaxed particles (30 μm or less) in a very fine alpha and beta eutectic, Figure 4. Reheating to a solid fraction of approximately 50% results in globularisation of the rosettes, with entrapped eutectic liquid pools present within the alpha phase, Figures 5a and 5b. There are also fewer smaller alpha particles and the euctectic is much coarser.

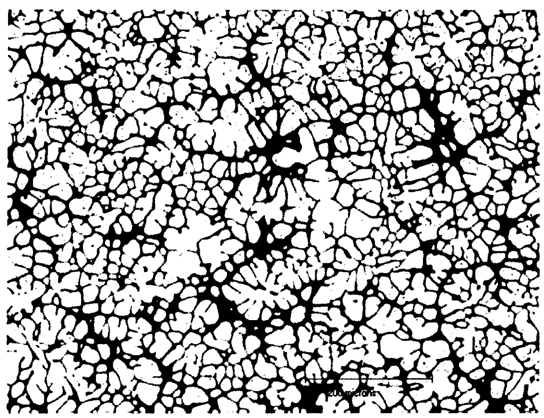


Figure 4 - Microstructure of as-received A357 rheocast bar

There is evidence of secondary crystallization of the alpha phase from the eutectic liquid, particularly near the edge of the box (Figure 5b). As expected, the microstructure of a specimen cut from a box cast from liquid metal does not display a globular alpha phase. At a region near the gate where the wall is thickest, a mixture of dendrites and rosettes and equiaxed particles are observed, Figure 6a.

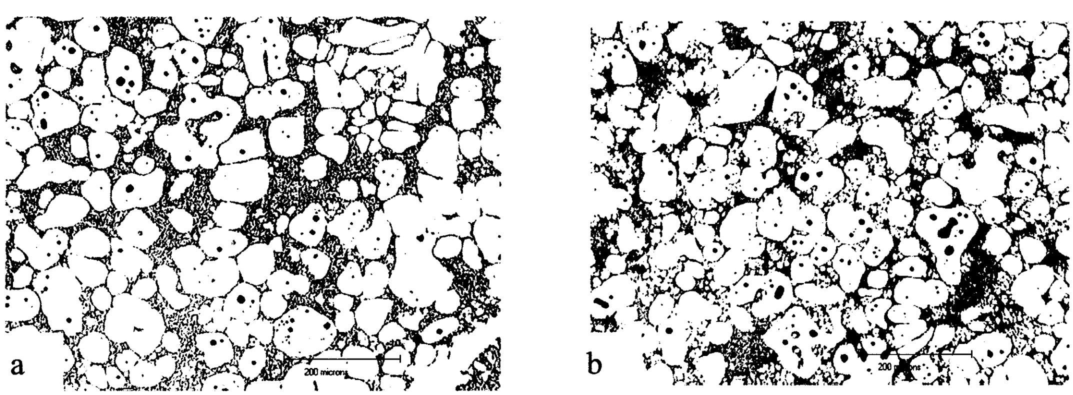


Figure 5 - Microstructure of SSM casting near gate (a) and at edge of box (b)

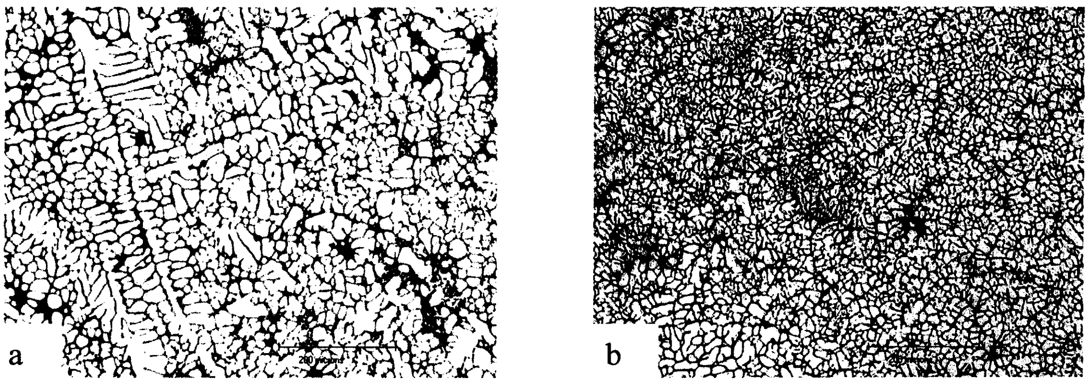


Figure 6 - Microstructure of casting from liquid at near gate (a) and at edge of box (b)

Near the edge of the box where the wall is thinnest, the particles are significantly finer and equiaxed (15 mμ or less), Figure 6b . Thus, unlike the semi-solid material, the shapes and sizes of the alpha particles in box cast from liquid metal are influenced by the solidification rate as the metal travels through the mould cavity. In the forged component shown in Figure 7, the sizes of the alpha particles are similar to those observed in Figure 5 as the same billet reheating procedure was used. However, at the locations from which these micrographs were taken, there is less eutectic liquid between the particles, in consistence with a slightly lower forming temperature used.

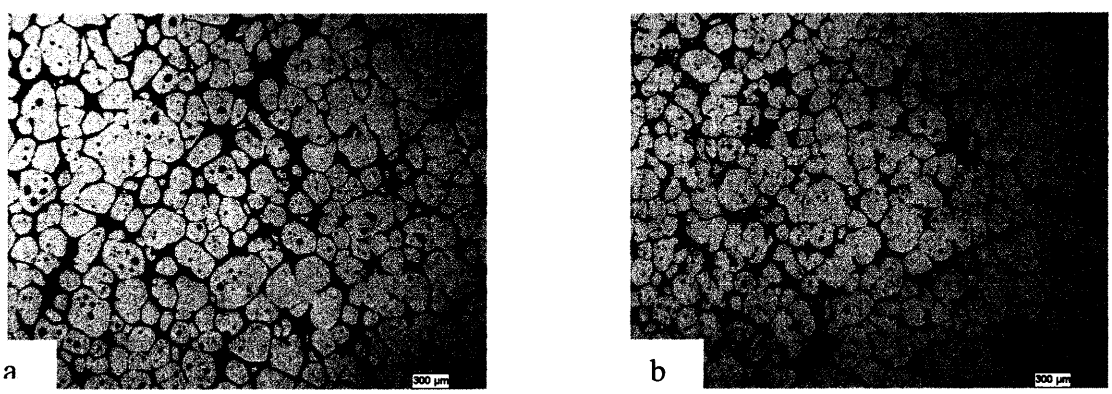


Figure 7 - Microstructure of forging at locations indicated in Figure 3 (a is near mid-section of the periphery of disc; b is at mid-section the center)

Tensile Properties

Comparative average 0.2% yield and ultimate tensile values of sub-sized ASTM specimens from semi-solid and liquid metal cast components as well as forged components are shown in Table 1.

Table 1: Yield and Tensile Strengths

Specimen	0.2% Yield Stress, MPa	Ultimate Tensile Strength, MPa
SSM Die Cast	102	179
Liquid Metal Die Cast	112	172
SSM Die Cast, T5*	206	249
SSM Forged	117	195

T5 : Water quenched + 6 hours at 170 ° C

In the as-formed condition, these values are rather similar for the semi-solid and liquid specimens while those of the forged specimens are somewhat higher. Values up to 25% higher in semi-solid cast A357 test bars have been reported (15). It is evident that heat-treatment of components to the T5 condition will very significantly enhance their yield and ultimate tensile strengths. The T5 condition is particularly attractive from the cost standpoint as the yield strength can almost be doubled by a relatively simple heat-treatment. Attempts to measure elongation values of these sub-sized ASTM specimens were met with limited success as values obtained varied from 2-12%. Further work will be required to investigate the cause of these variations.

CONCLUSIONS

A357 billets suitable for forming with a temperature gradient of less than 10 °C can be prepared by reducing power input into the coil over several stages in the semi-solid phase.

Rosette and equiaxed alpha phase particles in the rheocast feedstock alloy become globular upon reheating; unlike particles found in liquid metal die cast components, they are larger and their sizes do not vary with solidification rate.

Optimal parameters for casting and forging of a 1.4 kg box component and 1.5 kg disk component have been developed.

The as-cast 0.2% yield and ultimate tensile strengths of liquid metal cast, semi-solid cast and forged components are similar; T5 heat-treatment vastly enhance these properties.

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