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Hardness control of Al–Si HPDC casting alloy via microstructure refinement and tempering parameters

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ABSTRACT

Analysis of the effect of microstructure refinement, water quenching, natural ageing as well as T5 and T6 tempers on macro-hardness development of the hypereutectic HPDC Al–Si based alloy was performed. Duration of casting holding at room temperature after its removal from the die, and prior to subsequent temper operation had a measurable effect on casting macro-hardness. Such finding underlined the need for tighter control of parts handling between casting and heat treatment operations. Water quenching after casting de-molding operation increased alloy macro-hardness in naturally aged as well as T5 temper conditions but did not have any effect on macro-hardness after T6 treatment. T5 temper carried out after casting de-molding and water quenching from 380 °C enabled on average approximately 9 to 19% macro-hardness increase as compared to the T1 condition. Microstructure refinement had a minor effect on macro-hardness increase but the measurements of the α-Al matrix micro-hardness needed to be used to demonstrate this effect. Compared with T6, the T5 temper offered up to approximately 20 to 60% shorter process duration and could offer potential cost reduction gains achieved at the expense of lower macro-hardness. Microstructure refinement did not have the effect on T6 casting macro-hardness.

1. Background

Light-weight Al–Si based alloys are considered to be one of the key engineering materials used for cast automotive powertrain applications due to their unique combination of structural and service characteristics. Particularly, hypereutectic Al–Si alloys containing Si in a concentration above 12 wt.%, represent materials of choice for applications such as linerless engine block (i.e., without cast iron sleeve) and pistons. Superior performance characteristics of these alloys are achieved with a combination of wear resistance and thermal conductivity that in turn impacts engine's cooling characteristics [1–4]. Tribological properties of the hypereutectic alloy are mainly controlled by the primary Si size, distribution, exposure height from the aluminum matrix and overall alloy hardness [5]. The alloy macro-hardness is predominately affected by the volume fraction as well as refinement level of primary and eutectic Si in addition to hardness of the aluminum matrix. The hardness of the aluminum matrix is controlled largely via precipitation strengthening of nano-sized Cu and Mg based phases [6,7]. Subsequently, maximizing casting hardness and assuring the given size and distribution of primary Si are key process optimization parameters required to meet in-service requirements. The industrial practice of engine block manufacturing requires hardness of approximately 74 HRB and a primary Si size of approximately 20 μm as one of the acceptance criteria's needed to meet the cylinder bore surface wear resistance requirements [5,8].

Hypereutectic Al–Si based alloys are typically cast using Low Pressure Permanent Casting (LPPC) or High Pressure Die Casting (HPDC) technology [2,7,9]. Recently, vacuum processing is being used to minimize the content of gas porosity enabling the application of subsequent heat treatment processing [10–12]. In the HPDC process, liquid metal is ladled into the shot sleeve and injected into the water-cooled die where it rapidly solidifies under hydraulic pressure. The actual pressure value depends on specific equipment configurations and could be up to approximately 120 MPa with the melt flow velocity between 30 and $60~\mathrm{m\,s^{-1}}$ (100–200 km/h) at gates [13,14]. The resultant casting microstructure is a function of the casting process parameters. Its microstructure refinement level is typically expressed by SDAS (Secondary Dendrite Arm Spacing) of α-Al matrix and size of primary Si. The solidification rate inside the die cavity is among key factors impacting the refinement level of primary Si, solute segregation as well as degree of solid solution saturation [7,15–18]. Next, when casting temperature drops below solidus, casting is ejected from the die cavity, followed by the water quenching operation. After completion of these steps, casting is ready for further post-processing including T5 and T6 or T7 tempers. Specific temper selections depend on the component's final requirements. Water quenching after the de-molding operation is typically used to achieve the following: i) to cool down the casting to ease its handling operation, ii) to retain some degree of solid solution resulting

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from a non-equilibrium solidification in order to prevent the diffusion of the alloying elements. Industrial practice indicates that i) is preferred while ii) is seldom discussed in technical literature leaving this subject open for future studies [19–21]. Any machining operation for such near-net-shape HPDC parts is typically performed after heat treatment and requires casting to be dimensionally stable [6].

Recent developments on vacuum assisted HPDC technologies allowed for the subsequent application of T6 or T7 tempers, without the risk of blistering, in order to further increase casting hardness needed to meet tribological requirements [22]. The T5 treatment is cost effective compared with T6 or T7 tempers due to its shorter process duration and lower capital investment requirements. Such savings are achieved via elimination of solutionizing treatment as well as water quenching performed prior to the artificial ageing operation. The solution treatment can last between approximately 4 h down to 30 min depending on casting microstructure refinement [22–24]. However, the downside is that hardness of T5 heat treated castings is lower as well as less consistent for various casting sections as compared with T6 temper.

The effect of water quenching after the de-molding operation on subsequent casting mechanical properties is not well reported in technical literature nor is it well understood. This is particularly true for castings having varying microstructure refinement levels corresponding to different solidification rates [21,25,26]. Recently published papers deal typically with the effect of solidification rate on structural characteristics and the development of mechanical properties with cooling rates equivalent to sand casting operations [27–31].

Lumley et al. [32] conducted studies on applicability of low temperature solution treatment for die cast parts made from hypoeutectic 380 alloy (Al–8.5%Si–3.5%Cu–0.1%Mg). Some limited results were shown for T5 temper where the die cast parts were rapidly air cooled after casting operation and directly aged at 150 °C. The majority of Lumley's work focused on optimization of T6, T7 and T4 tempers with varying solutionizing conditions but aspects of solidification rate and quenching parameters after de-molding were not investigated. Sjölander et al. [30] investigated the effect of microstructure refinement as controlled by the solidification process (SDAS between 10 and 51 μm) on artificial ageing response of Al–Si–Cu–Mg alloy subjected to the T6 treatment. It was pointed out that microstructure refinement has a small influence on the yield strength as long as the solution treatment parameters are adjusted to achieve the complete dissolution of intermetallic phases and homogenization. It was reported that elongation at the fracture was improved by increasing the microstructure refinement level. Sjölander's investigation is not directly related to the present study but gives some additional insight on key material characteristics after T6 temper, particularly as a function of the microstructure refinement (solidification rate).

The effect of natural ageing, i.e., the duration of time the castings are held at room temperature after completion of the de-molding operation and prior to a heat treatment process is not well reported. Some studies are available but they describe the effect of natural ageing after completion of solutionizing treatment and prior to artificial ageing operation (T6 temper). Daswa et al. [33] investigated the effect of natural ageing i.e., delay between quenching after solution treatment and artificial ageing ranging from 0 to 135 days for 6xxx series alloys cast using rheo HPDC process. It was concluded that pre-ageing time has a negative or positive effect depending on the composition of the alloy as well, ageing times as short as 1 h can affect the T6 hardness. The negative effect of pre-ageing is attributed to the clustering of solute atoms forming at room temperature. It was pointed out that precipitates that develop directly from such clusters are coarser than these developed in alloys artificially aged right after the quenching operation.

In another study, Sjölander et al. [34] conducted the analysis of the effect of natural ageing on the artificial ageing respond of Al–Si–Cu–Mg casting alloys with SDAS of approximately 25 μm. Such microstructure refinement corresponds to the coarser section of parts made using the die-casting process. In this study, it was found that direct artificial ageing carried out after a solution treatment and water quenching gives the highest yield strength. Moreover, the duration of natural ageing ranging between 0 up to 3 weeks significantly affects the T6 ageing characteristics. This includes shortening the time needed to reach the peak, as well as peak strength values. Since Sjölander's paper does not address scenarios of the present study (water quenching after de-molding, varied microstructure refinement and T5 temper) it cannot be used directly as a reference. Nevertheless, this paper brings interesting insights on the effect of natural ageing on casting characteristics.

Gaps in the existing knowledge create opportunities for future research on solidification rates (microstructure refinement) that are equivalent to semi-permanent or permanent casting technologies used to manufacture a variety of powertrain components for the automotive industry. The objective of this work is to evaluate the hardness development of the hypereutectic Al–17%Si–4.5%Cu–0.5%Mg based alloy subjected to T5 and T6 tempers and to quantify the effect of microstructure refinement, natural ageing and water quenching after a casting de-molding operation.

2. Experimental procedure

2.1. Casting solidification experiments

The Al–17%Si–4.5%Cu–0.5%Mg based hypereutectic alloy known as 2nd generation DiASil™ was used in this study with a chemical composition as presented in Table 1. All concentrations of alloying elements reported in this work are expressed in wt.% unless otherwise specified. Such hypereutectic Al–Si alloy is intended for a variety of high pressure die-casting applications in the automotive industry [2,3,15]. Due to the complex melt temperature profile, as observed during the HPDC process and the difficulty in replicating it during the laboratory experiments, a simplified approach was taken to cast this alloy into a taper water-cooled copper mold. A schematic drawing of the mold with the description of its key elements is presented on Fig. 1. This mold was designed to be split open permitting to release cast part into the quench tank at the predetermined temperature with in-situ temperature measurements. Wedge shaped cast parts had a weight of approximately 7 kg, with variable section thickness from 10 to 75 mm and associated microstructure refinement with SDAS from 7.6 ± 1.1 to 16.1 ± 3.2 μm and primary Si size varying from 14.9 ± 3.2 to 30.3 ± 4.3 μm. These values were obtained based on the microstructure measurements performed between the top and bottom parts of the wedge casting along the distance of approximately 120 mm with measurements done at 5 mm increments. Such values of the SDAS and equivalent diameter of primary Si, as obtained in this study, were typically observed in the cast parts manufactured using HPDC or LPPM processes [8] [35]. The investigated alloy was melted as per standard practices described elsewhere [9,17]. The wedge copper mold was instrumented with K-type thermocouples for in-situ temperature measurements during the casting and water quenching operations. Selected process parameters as well as corresponding heat treating T temper codes are presented in Table 2 [36]. Thermal analysis during the melting and solidification cycles was carried out to determine the alloy liquidus temperature as per methodology described elsewhere [17,37].

Table 1
Average chemical composition of the hypereutectic DiASil™ Al-17%Si based alloy (wt%).

Si	Cu	Mg	Zn	Fe	Mn	Ni	Sn	P
17.0	4.5	0.5	0.05	0.4	0.05	0.05	0.05	0.0085-0.011

Note: The targeted P concentration was 0.01%.