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EFFECT OF COOLING WATER QUALITY ON DENDRITE ARM SPACING OF DC CAST BILLETS

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Abstract

For a given alloy chemistry & casting technology, the quality of a billet produced through DC (Direct Chill) casting route is largely defined by the DAS (Dendrite arm spacing). DAS in turn, is determined by the cooling rate and local solidification time. The cooling rate is influenced by the quality & quantity of water besides casting speed and melt temperature. This paper focuses on the relationship between the quality of cooling water & the resultant DAS during production of DC cast billets. An empirical relation is derived to indicate the influence of cooling water characteristics on the DAS, based on a mathematical model supplemented by experimental investigations. The model has been validated in plant scale trials.

Introduction

The quality & properties of cast products strongly depend on microstructure development during solidification. The DAS is a fundamental characteristic of the microstructure and has been used over the years as a means of fineness and, hence is a measure of the quality of cast products. It has also been established that DAS exercises a significant influence on extrudability. Therefore it is of great interest to analyze the inter dependence of the DAS and process parameters for improving product quality & development of superior methods for quality castings. Cooling rate and solidification time have a dominant impact on DAS. A quantitative understanding of the cooling rate experienced by the component during solidification is necessary.

Heat transfer rate of an alloy during DC casting depends on the speed of casting, casting temperature, quantity & quality of cooling media. During steady–state stage of casting, the shape and dimensions of the solidification region remain constant. Shape & dimensions determine thermal gradient which is responsible for structural homogeneity in the castings. Thus, cooling water used in DC casting process plays an important role in controlling the cooling rate during the solidification process.

The influence of water quality has been analyzed by many researchers. In one of the first papers on the subject, Ho Yu [1] has shown from his missile test that dissolved air, surfactant, cationic poly electrolytes & oil content, all have an adverse effect on the heat transfer rate. Langlais et al [2] have also inferred that oil content & flocculants beyond 10 & 1000ppm respectively, reduce cooling rate. The effect of composition, temperature and flow rate of cooling water on heat transfer has been studied by Grandfield et al [3] through experiments.

Numerous solidification studies have been developed with a view to predict microstructural parameters. Many scientists have attempted to quantify the interfacial heat transfer during solidification in terms of heat transfer coefficients [4] or heat flux [5].They have highlighted several factors that affect heat transfer during DC casting process and in turn the microstructure. Influence of process variables such as mold surface roughness, mold material, superheat, alloy composition & lubricant on heat transfer & cast structure has been studied by C.A. Moujekwu et al [6]. They have proposed an empirical transient heat flux model to take the above variables into account. Dominique Brochord et al [7] have tested the general predictability of dendrite arm spacing for unidirectional solidified binary alloys through experiments. They have concluded that for prediction of DAS, the exponent -1/3 in the exponential relationship of cooling rate with DAS is adequately represented in both steady & unsteady state heat flow.

Using empirical relationships, the dendrite arm spacing & degree of homogenization have been predicted by C.Devdas et al [8]. The effect of casting speed, super heat & metal height on the heat transfer has also been analyzed by them. The study of Ivan Todaro et al [9] also focuses on the relationship between DAS and local cooling rate. They have also been able to correlate DAS with the mechanical properties of the cast. The work of Bomberger et al [10] have demonstrated that increase in silicon content of an aluminium alloy reduces cooling rate and hence has an influence on DAS. Mark Easton et al [11] have been able to predict SDAS (Secondary Dendrite Arm Spacing) for multi-component aluminium alloys and have inferred that grain refiner has little effect on SDAS; rather composition of liquid at the temperature at which SDAS is determined is the most influencing factor.

The aim of the present work is to determine the effect of the quality of water on heat transfer rate during direct chill casting of billets through hot top Air slip casting system and to correlate the water quality variables with SDAS.

Experimental Procedure

Experiments were carried out in two stages.

A. Laboratory experiment

A cylindrical sample of diameter 2" & length 12" was machined from the middle part of an AA6063, 7" billet. It was heated up to a predetermined temperature in a muffle furnace (equipped with a temperature controller) & soaked for 30 minutes to ensure uniform temperature distribution through out. Thereafter, the heated sample was quickly removed from the furnace and immersed in a fixed quantity of cooling water. The instantaneous temperature of the sample was obtained by a K-type thermocouple located at the axial & radial centre of the sample. A data logger system (Yokogawa-DX2008) recorded the temperature at a sampling rate of 20 Hz.

Water quality was varied by changing temperature, hardness, and oil content. Several trials were carried out by changing the value of one quality variable at a time and the corresponding cooling curves were recorded. In all the trials, constant water quantity was maintained.

DM (demineralised) water at 30^{0}C was used as the base case. For the purpose of the experiment, the quality of DM water was changed by

I. Raising the temperature.
II. Addition of salts to raise hardness
III. Addition of lube oil

The matrix of the different experimental conditions are shown in table I.

Table I. Experimental cases

Cases	Water temperature (WT), ^{0}C	Water hardness (HD) ,mg/L	Oil (OL), ppm
1	20	0	0
2(base case)	30	0	0
3	40	0	0
4	60	0	0
5	30	70	0
6	30	150	0
7	30	300	0
8	30	0	50
9	30	0	100
10	30	0	150

B. Shop floor experiment

AA6063, 7" diameter billets were cast using 3 different parameters as described in table II. The casting recipe of a 7" billet was chosen as base case. Case-2 and 3 conditions were achieved by fitting one 7" mold with its starting block in a 6" diameter billet casting table and again another one in an 8" casting table.

Table II. Different casting parameters

Cases	Water flow rate, lpm	Casting speed, mm/min	Pouring temp, ^{0}C	Water temp, ^{0}C
1 (base case)	78	126	705	38
2	68	145	708	38
3	130	102	706	38

Cooling water of hardness 130 mg/L and oil ppm 40 ppm was used for all the three cases. The surface temperature of the billet during steady state (i.e. after 1 meter of billet casting) was measured at three fixed points at a particular time. The temperature readings were also confirmed through thermographs. Pool depth was measured after steady state regime during the three cases.

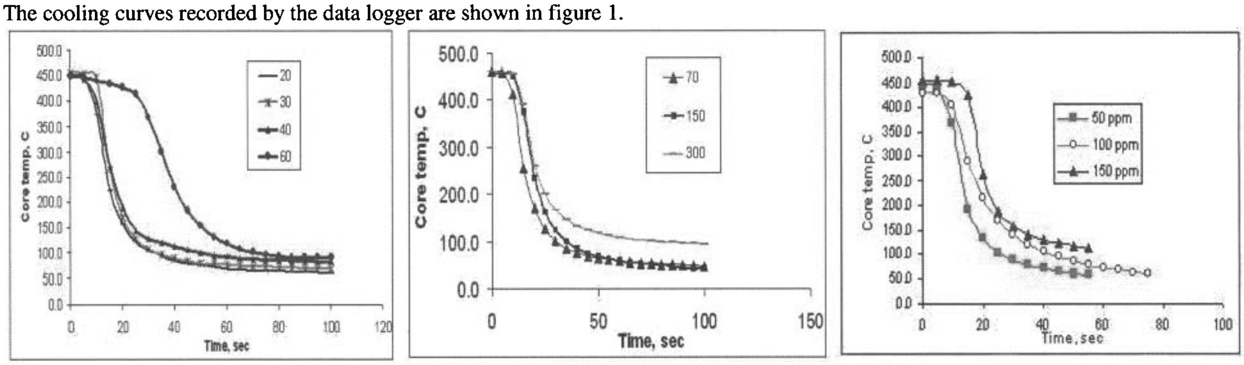
Metallographic studies were conducted on mid radius regions of samples obtained from the central portion of the billets. SDAS was measured by use of Olysia Image Analyzer Software.

Results & Discussion

The results obtained from experiments were utilized & analyzed in four stages.

A. Correlation Between Water Quality Variables & Surface Heat Flux

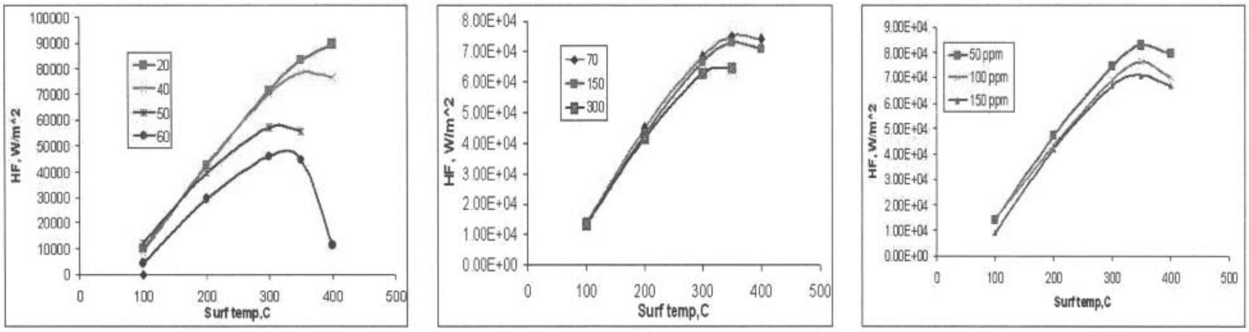
The cooling curves recorded by the data logger are shown in figure 1.



(a) (b) (c)

Figure1. Cooling curves for different (a) water temperature, (b) hardness, (c) oil content

An inverse heat conduction model [12] was used to extrapolate heat flux as a function of surface temperature. The heat flux values with the corresponding surface temperatures (pool boiling curves) are illustrated in fig 2.



(a) (b) (c)

Figure 2. Change of heat flux with surface temperature at different a) water temperature, b) hardness, c) oil content.

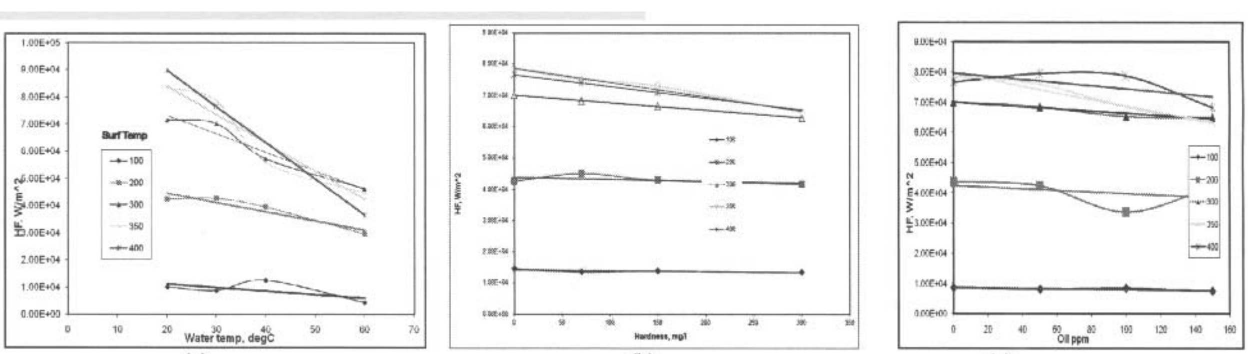
The relatively constant temp plateau at the beginning (depicted in the cooling curves (fig 1)) can be attributed to film boiling, in which a vapor blanket insulates the surface from cooling water. It is evident from the fig 2(a) that higher water temp decreases critical heat flux value and promotes film boiling at lower surface temp. The effect of rise in water temperature from 20^0C to 30^0C had a very little influence on heat flux. This observation also matches with the findings of Langlais et al [2] & Grandfield et al [3].

In a salt solution, cations and anions play a major role in formation of bubbles in a pool boiling. Cations reduce bubble coalescence whereas anions favour it thereby promoting film boiling. The reduction in critical heat flux in fig 2(b) indicates the pronounced effect of anions in the water. Cations are sometimes added in the water to promote nucleate boiling over film boiling.

The oil in water forms a water-oil emulsion that was found to have lowered the leidenfrost point thus promoting film boiling as seen in fig 2(c). In general critical heat flux decreases when oil content in the water is raised because of diffusion in an oil enriched region surrounding the growing vapor film.

The rise in water temp because of insufficient cooling and seasonal variation can be seen to affect cooling rate significantly. The scale formation in the water pipe lines because of repeated recycling and inadequate water treatment contributes to increase in hardness in the casting station. Oil content rises when there is leakage into the water system. All these factors promote film boiling & diminishes heat transfer rate during DC casting thereby affecting solidification.

In order to assess the extent of influence of these factors on microstructural parameter (DAS) of castings, correlations have been derived. From the experimental & model data, correlations could be formed between water variables & heat flux at various surface temperatures (fig 3).



(a) (b) (c)

Figure 3. Change of heat flux at different surface temperatures for different a) water temperature, b) hardness, c) oil content.

Considering the combined effects are additive, the trend line equations for different variables are combined to formulate generalized equations containing all the water quality variables (table III) for specific surface temp in the form,

$$HF = HF\ (base\ case) + slope\ of\ temp\ plot * (WT - 30) + slope\ of\ hardness\ plot * HD + slope\ of\ oil\ plot * OL \quad (1)$$

Table III. Heat flux at different surface temp

Surface temp, ^{0}C	Combined equations for HF
100	HF = 8.6e3 - 128.71*(T- 30) – 3.17*HD - 6*OL
200	HF = 4.27e4 - 340*(T - 30) - 6.1847* HD – 27.6*OL
300	HF = 7.01e4 - 679.43*(T - 30) - 24.237* HD – 37.03*OL
350	HF = 7.85e4 - 1038.9*(T - 30) - 45.562* HD - 108*OL
400	HF = 7.66e4 - 2002.7*(T - 30) - 37.367* HD – 51.29*OL

The strength of the equations were tested with heat flux values predicted by lab model (from temperature measurement) in two different water trials (T= 36 & 34 ^{0}C, HD=260 & 50 mg/L , OL= 10 & 50 ppm) in fig 4. The empirical relation found to be closely matching with predictions for combination of all variables.

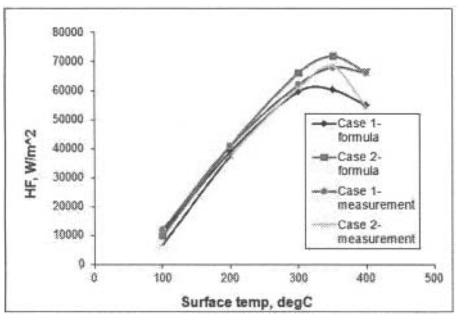


Figure 4. Comparison of formula output with model

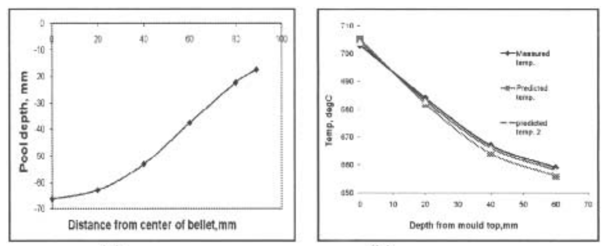
Absolute heat flux values obtained in the experiment pertains to the sample geometry and experimental conditions, which are different from actual billet casting. The geometry of the experimental set up possesses cylindrical symmetry with billet casting. The rate of change of heat flux due to change of water quality is considered here to be independent of size & process parameters.

The rate of change of heat flux values were obtained from the relationship of various slope values of water quality (noted in table III) and surface temperature, for each variables. These were used as correction factors to the heat flux input table of a billet model to get changed set of heat flux data for different water variables. These would be put as boundary conditions for the billet model to generate cooling profile in the billet and would predict cooling rate to be used in stage 'C'.

B. Development of Billet Casting Model

A 2-D transient thermal model based on finite element method was developed by using ANSYS software for the 7" (AA6063) billet casting. The casting parameters were as per the base case shown in table II. The model was simulated for case 2 and 3 of table II for validation. Material property was taken from Ref [13] and fluid flow aspect was not considered. Equivalent specific heat approach has been adopted.

The measured pool depth (average of 5 measurements during steady state) was found to be 64 mm and matched well with the predicted solidification profile (figure 5 (a)). In order to further validate the model, center temperature of billet at three different depths in the sump was measured by dipped in thermocouple and found to be in close agreement with model predictions (fig 5(b)).



(a) (b)

Figure 5. Measurement vs. model prediction a) pool depth, b)sump temp

C. SDAS & Cooling Rate:

Secondary dendrite arm spacing (λ) which has an impact on the billet properties, is known to vary inversely with cooling rate during solidification as per formula [14, 15],

$$\lambda = AT_c^{-n} \qquad (2)$$

Where, 'A' is a constant for a particular casting technology, alloy and size of casting. 'Tc' is the cooling rate. The exponent 'n' lies in between 0.2 to 0.4 for most of the aluminium alloys [14, 15].

The average cooling rate in the solidification range at mid radius region was computed by the billet model for the three cases mentioned in table II. Measurements were carried out with the samples representing the corresponding three cases for SDAS. Computed Tc & measured SDAS for the corresponding cases are tabulated in table IV.

Table IV. Computed cooling rate and measured SDAS

Case	Model predicted Tc at mid radius point, (^{0}C/ sec)	SDAS measurement (Average of 10 measurements) µm
1	0.75	20
2	1.05	18
3	1.5	16

The correlation derived from the measurement values through curve fitting (Fig.6) is expressed by the equation,

$$SDAS = 18.25T_c^{-0..322} \quad (3)$$

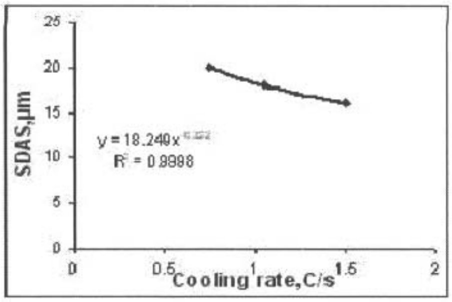
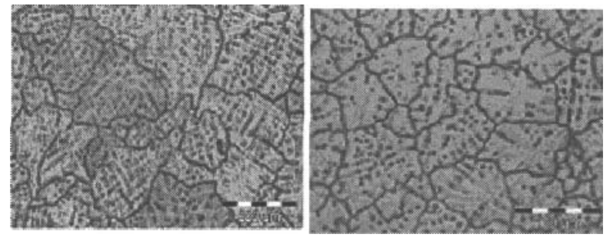


Figure 6. Cooling rate Vs SDAS

The micrograph of the two 7" billets (mid radius region) are shown in figure 8.

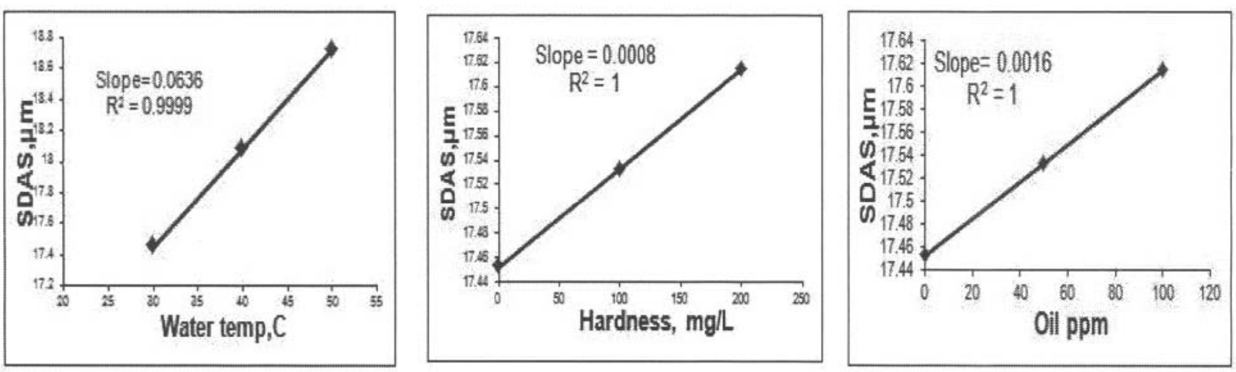


(a) (b)

Figure 8. Micrograph showing dendrites (etched with Kellers reagent) for (a) case-2, (b) for case-3, of table III.

D. Water Quality & SDAS

After incorporating the corrections to the heat flux on account of water quality, 9 hypothetical cases of varied water quality was formulated. The billet model was simulated with the 9 cases and was able to predict 9 different cooling rates. SDAS was calculated by using equation (3) for all the hypothetical cases and plotted in figure 7.



(a) (b) (c)

Figure 7. Change of SDAS with water quality at different (a)water temperature(HD=0,OL=0,) (b) hardness(WT=30,OL=0), (c) Oil content (WT=30,HD=0).

As seen from the figures 7, the SDAS varies linearly with the quality parameters (varying one at a time). SDAS of base case (WT = 30, HD=0, OL=0) was found out to be 17.453. Thus, a generalized composite correlation has been derived considering the fact that the effect of all variables are additive in nature as shown below.

$$SDAS = 17.453 + 0.0636*(WT - 30) + 0.0008*HD + 0.0016*OL \quad (4)$$

This equation was reliable for standard casting recipe of 7" billet as mentioned in case-1 of table I. The equation was verified during five shop floor castings with different water quality parameters. The calculated SDAS was found to be comparable to the values obtained from metallographic measurements. The comparison is shown in table V.

Table V. Comparison of calculated SDAS with measurements

Water Temp ^{0}C	Hardness Mg/l	Oil ppm	SDAS Calculation µm	SDAS (Average of 10 measurements) µm
36	260	10	19.05	20
34	50	50	17.8	19
30	60	40	17.6	18
38	130	40	18.13	19
40	120	40	18.25	21

A 16% variation in SDAS could be observed during the trials in the shop floor. This would have an impact on homogenization as well as extrudability of billets.

Conclusion

The effects of water temperature, hardness, oil content of the cooling water used in a DC casting process on the dendrite arm spacing of billets was investigated through experiment and modeling. An empirical relation was derived. This correlation has been tested in a plant scale DC casting station in order to closely predict dendrite arm spacing. The empirical relation serves as a useful tool for fine tuning casting recipe for different conditions of water quality. SDAS at mid radius of billet is specified by billet manufacturers to indicate the quality. Low and consistent SDAS helps the extruders to run the press with uniform parameters so as to maximize productivity. The variability of SDAS because of different cooling water quality during different seasons like summer, winter or rainy seasons can be judiciously taken care of by this tool.

From the results of the study following conclusion can be made:

i. The water temperature has a very strong influence on the cooling rate of the casting and has maximum impact on SDAS. SDAS increases with increase in water temperature.

ii. Hardness and oil content in cooling water also increases SDAS in DC casting billets, but the effect is minimal.

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