# Effect of Cooling Rate on Mechanical Behaviour of Bulk Cast of A380 Aluminium Alloy

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***Abstract*** **- One of the major factors that influence the mechanical properties of the cast alloy is the cooling rate during the solidification process. The objective of the present research work was to examine the effects of cooling rate on the mechanical properties of the A380 aluminum alloy cast. To study the variations in the mechanical properties with respect to cooling rate, the alloy was cast by conventional air-cooled and water-cooled methods. In this study the mechanical properties like tensile strength, compressive strength and impact strength of both air-cooled and water cooled cast specimens were tested and the results were compared. Increases in tensile and compressive strengths of the water cooled cast specimen have been encountered from the present work. This result reveals that increase in cooling rate leads to enhancement of the mechanical properties and also the disparity in them at various regions of bulk castings.**

**Keywords: Aluminium alloy casting, Eutectic silicon, Copper aluminide (CuAl2), Cooling rate, Solidification rate, Tensile strength, Compressive strength, Impact strength.**

## I. INTRODUCTION

In the recent years, research works relating to solidification of cast alloys with high cooling rate have come to be progressively more important. Compared with conventional casting techniques, rapidly solidified cast products have a very good amalgamation of strength and elongation, which is basically due to finer grains and homogenous microstructures. By refining the microstructure of cast aluminium alloys, the high temperature mechanical performance would be improved.

W. Kurz, B. Giovanola and R. Trivedi [1] have developed model and described that the rate of solidification or cooling rate influences the solubility limits and the grain structure in Al-Si alloy castings. A. Venkatesan, K. Suchitra and A.Rajadurai [2] made attempt to measure the air-gap formed between mold and cast during solidification and reported that the air-gap significantly affect the cooling rate and which in turn affect the properties of cast alloys. S.G. Shabestari and H. Moemeni [3] investigated the effect of solidification conditions on microstructure and mechanical properties of Al-Si-Mg alloy. They found that the eminence of the microstructure of cast aluminium alloy depends on casting methods and solidification and/or cooling rate. B. Dutta and M. Rettenmayr [4] have studied the effect of cooling rate on solidification behavior of aluminium alloy and reported that, an increase of the cooling rate results in refinement of secondary intermetallic phase.

The cooling rate shows an apparent influence on the microstructure of the hypereutectic aluminium alloys as indicated by J. Zhang et al. [5]. Dr. Zeyad and D. Kadhim [6] investigated the effect of cooling rate on mechanical properties of eutectic and hypo-eutectic Al-Si alloys and proved that the strength and impact resistance of these alloys are greater when poured in a metal mold than that when it poured in a sand mold. W.R. Osorio et al. [7] have identified that mechanical properties are influenced by the microstructural arrangement L.A. Dobrzański et al [8] have found that increase of solidification rate has direct impact on hardness of Al-Si-Cu alloys. The same author studied effect of cooling rate on the solidification behavior of AC AlSi7Cu2 alloy and reported that, an increase of the solidification rate lead to an increased number of nucleus [9] that affects the size of the grains. Musa Gogebakan et al. [10] have stated that the rapid solidification technique has considerable interest for the development of high-strength alloys for service at elevated temperatures.

Cast A380 aluminium alloy is used extensively by the automotive, aircraft and chemical industries because of it's best castability, high strength and low cost compared to other aluminium alloys. M. Voncina et al. [11] studied the grain refinement of A380 alloy and stated that the presence of copper enhances the mechanical properties of this alloy. Literature was done to the best of the knowledge of the authors and found that, the influence of solidification and/or cooling rate on bulk cast of A380 has not been reported. Hence the aim of the present research work is to examine the influence of solidification rate on mechanical properties of bulk casting of this alloy. The composition of alloy is given in Table I.

TABLE I
Chemical Composition of A380 Aluminium Alloy

| Chemical Elements | Cu | Si | Mg | Fe | Mn | Ni | Zn | Pb | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|---|
| Wt. % | 3.42 | 7.8 | 0.18 | 1.1 | 0.41 | 0.3 | 2.64 | 0.25 | 0.18 | Reminder |

## II. Experimental procedure

In this work copper is used as a die material for attaining the fast heat transfer during solidification. Fig. 1 (a) and (b) shows the schematic diagrams of conventional air-cooled and water-cooled gravity die setups.

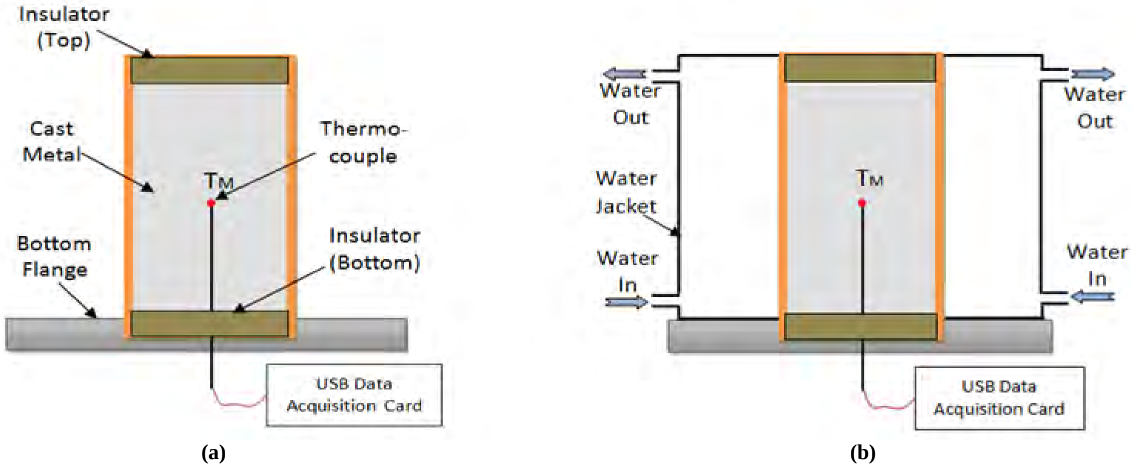



Fig. 1. Schematic representation of (a) Air-cooled setup (b) Water-cooled setup

The top and bottom of the die were insulated by asbestos discs; hence cooling will take place only through die wall. This setup helps to fix the simple boundary conditions (unidirectional) for the simulation work. The bulk cast examined in this research work was in cylindrical shape with 50 mm diameter and 100 mm height. Die wall thickness was chosen as 10 mm. The dimensions of water-cooled die are same as that of air-cooled setup. The diameter of water jacket was chosen as 140 mm. Water jacket contains two inlet ports and two outlet ports with 10 mm diameter. Cold water enters jacket from the bottom and extract the heat from the outer surface of the die, finally exit through the ports existing at the top.

Mineral insulated K-type thermocouples were used to measure the temperature at the mid of the cast, which is identified as $T_M$ in Fig, 1. Thermocouple was coupled with a computer controlled data acquisition system for recording the thermal history of the cast.

An alloy of A380 ingots were remelted in a graphite crucible using electric furnace. While transferring the melt from furnace to mold considerable heat loss occurs due to convective heat transfer to the atmosphere, hence the melt was superheated to 825°C (1517 F). Industrial de-gasser 19 was used to extract the unwanted gases from the melt, and furnace was purged using argon gas. After reaching the pre-set furnace temperature the molten metal was quickly transferred to molds with specified flow rate through funnel. Fig. 2 (a) and (b) shows the photographs of melting and pouring of alloy respectively.

**(a)**

**(b)**

Fig. 2. Photographic view of (a) Melting (b) Pouring

## III.RESULT AND DISCUSSION

The microstructure and mechanical properties of cast products are greatly influenced by the cooling rate during their solidification. Muthukrishnan Mohandass and Alankaram Venkatesan [12] have examined the influence of solidification rate on mechanical properties of Al-Si alloys. They found that the ultimate tensile and compressive strengths have increased with the increase of solidification rate. To confer the correlation and/or variance in cooling rates between the air and water cooled casting processes, the thermal data acquired by thermocouples ($T_M$) of both the techniques were plotted and discussed underneath.

### *A. Cooling Curve s Comparison*

Fig. 3 shows the comparative of cooling curves of air-cooled and water-cooled castings. From the cooling curves it is evident that the solidification of alloy takes place over a range of temperature rather than at a discrete melting point. From the figure it is seen that short freezing (solidification) occurred in water-cooled casting compared to air-cooled casting.

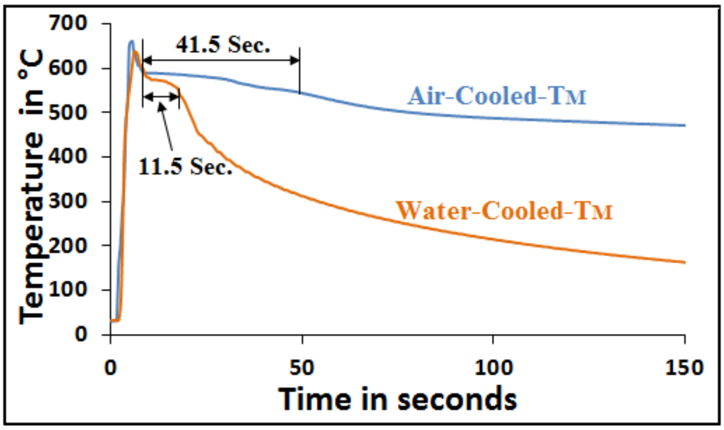


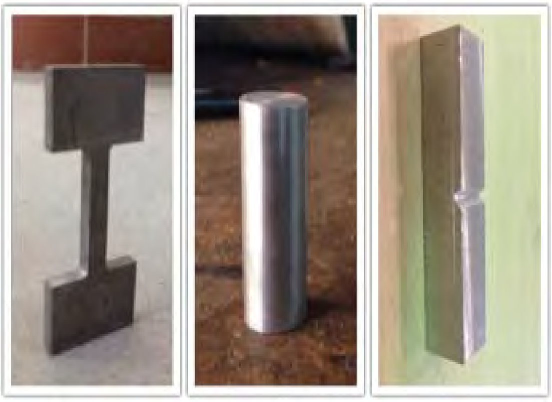

Fig. 3. Comparative graph between air-cooled $T_M$ data and water-cooled $T_M$ data

The time required for the change of phase from liquid to solid completed within around 11.5 seconds in case of water-cooled technique. On the other hand in case of air-cooled method the change of phase materialized over a long period of 41.5 seconds. The momentary phase change in water-cooled casting stimulates the nucleation of primary α-Al, eutectic and $CuAl_2$ grains concurrently at more points relatively compared to air-cooled casting system and thus water-cooled casting method produces castings with well refined grains.

### *B. Correlation between Solidification rate and Mechanical Properties*

Solidification is a phase transformation process during which enormous amount of heat energy released from the melt by means of conduction and convection. The solidification mechanism is directly related to the characteristics of alloys. W. Kurz [13] stated that solidification plays a vital role since it forms the basis for influencing the microstructure and hence improving the quality of cast products. The solidification rate has direct impact on formation of grains, shrinkage cavity and distribution of secondary and ternary phases. E. Karakose and M. Keskin [14] have reported that the rapid solidification increased structural and chemical homogeneity with extension of solid solubility. Hence it is evident that the increase in solidification rate improves the mechanical properties of the cast alloy.

A casting does not solidify suddenly throughout its entire mass, therefore the surface and core of the cast might have different structural morphology which leads to variation in mechanical properties along the radial direction of the cast considered in this study. Hence the test specimens are taken from the core (C) and the region near the surface (O). The specimens for tensile test are taken at regions C and O and are identified as 'TC' and 'TO' respectively. Similarly compression and impact test specimens are identified as 'CC', 'CO' and 'IC', 'IO' respectively. The tensile test specimens were prepared as per ASTM standard B 557M. The compression test specimens were prepared as per ASTM designation E 9-69a and impact test specimens were prepared as per ASTM standard E 399 (E23-07a). The tensile and compression testings were conducted using portable (5 ton capacity) Digital encoder-universal testing machine. Charpy method was used to examine the toughness. Fig. 4 (a), (b) and (c) shows the photographs of tensile, compression and impact test specimens respectively.



**(a)** **(b)** **(c)**

Fig. 4. Photographs of test specimens (a) Tensile (b) Compression (c) Impact

Fig. 5 shows the true tensile stress- strain curves of both air-cooled and water-cooled A380 aluminium alloy castings. The trend of tensile strength curves is almost similar for both water-cooled and air-cooled castings. From the figure it is evident that the alloy cast by water-cooled technique has greater tensile strength compared to air-cooled casting. The tensile test observations (UTS, YS and % of elongation) are given in Table II. Ultimate tensile strength (UTS) of 'TO' specimen reached the maximum of 360.27 MPa for water-cooled cast whereas as in case of air-cooled it was only 292.3 MPa. Similarly the UTS of water-cooled cast specimen 'TC' is greater (320.7 MPa) compared to air-cooled cast specimen 'TC'. Likewise yield strength (YS) is better in case of water-cooled casting and the percentage of elongation was found to be low for the water-cooled casting compared to the air-cooled one.

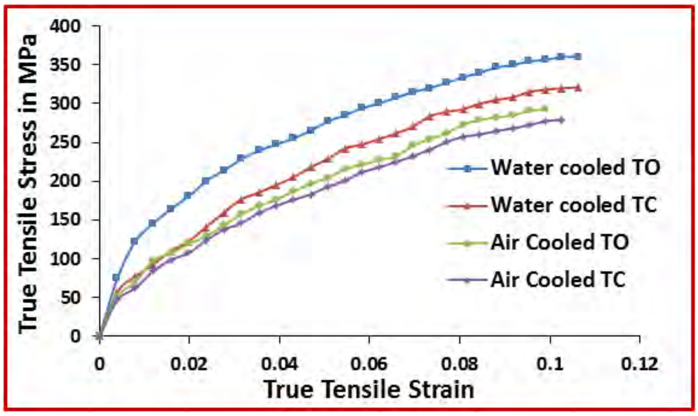
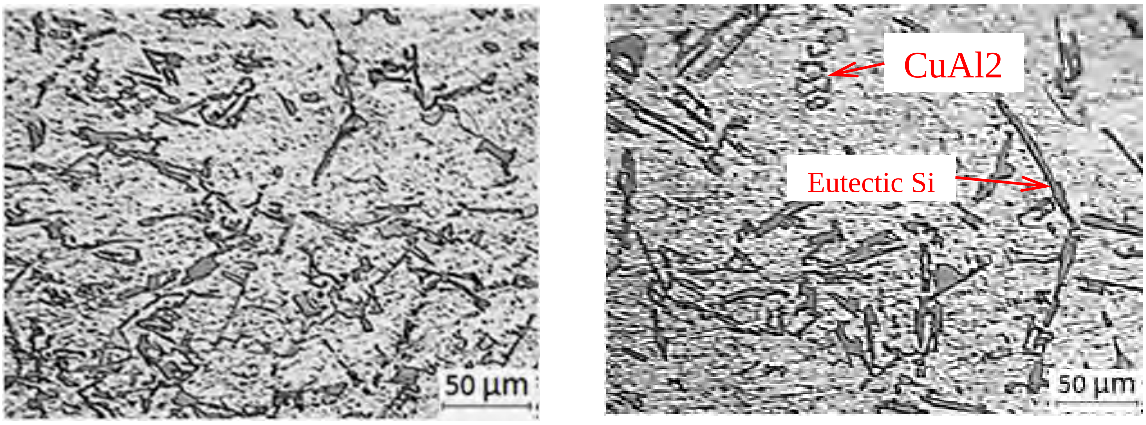



Fig. 5. True Tensile Stress-Strain curves

TABLE II
Tensile test data of A380 Alloy casting

| Specimen ID'S | | UTS (MPa) | YS (MPa) | % of elongation |
|---|---|---|---|---|
| **Water Cooled** | **TO** | 360.27 | 328.45 | 2.22 |
| | **TC** | 320.95 | 298.5 | 2. 84 |
| **Air Cooled** | **TO** | 292.3 | 276.12 | 3.1 |
| | **TC** | 279.32 | 263.6 | 3.78 |

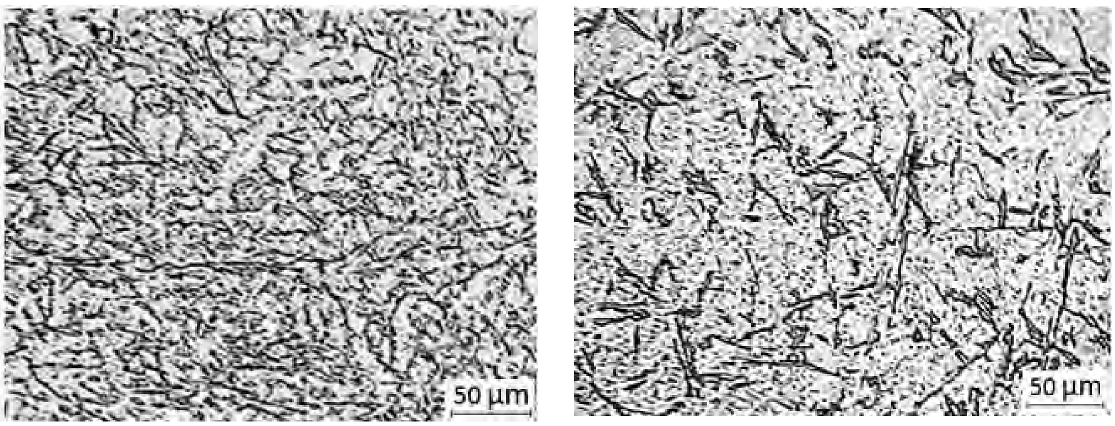
McFadden and S. Browne [15] have reported that the nature of cast microstructure influences the final properties of the alloys. When the casting cools, it does so progressively; the surface region solidifies first and the core region last. Fig. 6(a) and (b) shows the micrographs of surface and core regions respectively for air-cooled casting.




**(a)** **(b)**

Fig. 6. Micrographs of air-cooled casting (a) Surface region (b) Core region

In case of Al-Cu-Si alloy the formation of eutectic silicon and precipitation of copper aluminide (CuAl2) occurs during the solidification process. Large amount of fine and homogeneous distribution of eutectic silicon was found in the surface region micrograph Fig. 6 (a) due to immediate chilling effect which results in better tensile strength. Whereas in the core region the tensile strength of the alloy is less as eutectic silicon are found to be larger in size and non-homogenously distributed which is evident from Fig. 6 (b). Apart from that the course grains of CuAl2 was also observed in the core region, which is also one of the cause for the lesser UTS. Fig. 7 (a) and (b) shows the micrographs of surface and core regions respectively for water-cooled casting. It is observed that very fine eutectic silicon was formed in water-cooled casting when compared to the air-cooled casting due to the short freezing of alloy. As discussed earlier, short freezing occurs in water-cooled cast, which is evident from Fig. 3.




**(a)** **(b)**

Fig. 7. Micrographs of water-cooled casting (a) Surface region (b) Core region

The water circulated through the jacket induces immediate chilling effect at the surface region compared to core region which leads to the formation of very fine eutectic silicon. There is no evidence for the presence of CuAl2 particles in the surface region. Since the rapid cooling increased the solubility limit of the alloy. From the

Fig. 7 (b) it is observed that longer eutectic silicon scripts formed in the core region due to slower cooling compared to surface region. It is also found that CuAl2 is finely precipitated at the surface region of water-cooled cast compared to air-cooled cast. Reasonably in water-cooled casting very fine eutectic grains were obtained at both surface and core regions compared to that of air-cooled counterparts. The well refined eutectic grains increase the UTS and YS remarkably in the case of water-cooled casting.

Fig. 8 shows the true compressive stress- strain curves of both air-cooled and water-cooled A380 aluminium alloy castings. It is seen that the trend of compressive stress-strain curves is similar to that of tensile stress-strain curves.

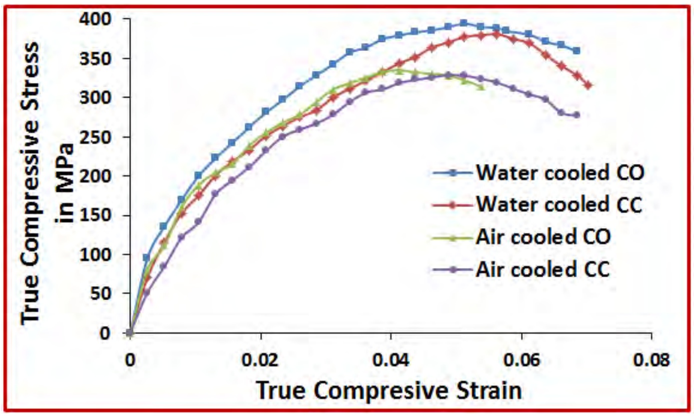



Fig. 8. True Compressive Stress-Strain curves

The ultimate compressive strength for water-cooled casting attained the maximum value of 394.1 MPa (335 MPa for air-cooled casting) at the surface region (specimen 'CO') and 380.8 MPa (328.8 MPa for air-cooled casting) at core region (specimen 'CI').

As conferred previously that due to immediate chilling effect at the surface region, large amount of well refined α-Al dendrites and eutectic silicon is formed for both water and air-cooled cast. Hence, the improved value of compressive strength was obtained in that region compared to core region. Relatively the water-cooled cast exhibits superior strength in both the surface and core region due to the short freezing of alloy.

Fig. 9 shows the toughness bar chart of both air and water-cooled castings. As per Hall-Petch equation, hardness of metals increases with the decrease of grain size. The surface region of both the castings is expected to have high hardness compared to core region which is due to the presence of finer grains. It is well known that the impact strength (toughness) is typically low for the materials with high hardness (brittle) and therefore, the core region has superior toughness compared to surface region in both the cases. Relatively air-cooled cast has poor hardness which leads to the higher toughness which is evident from Fig. 9.

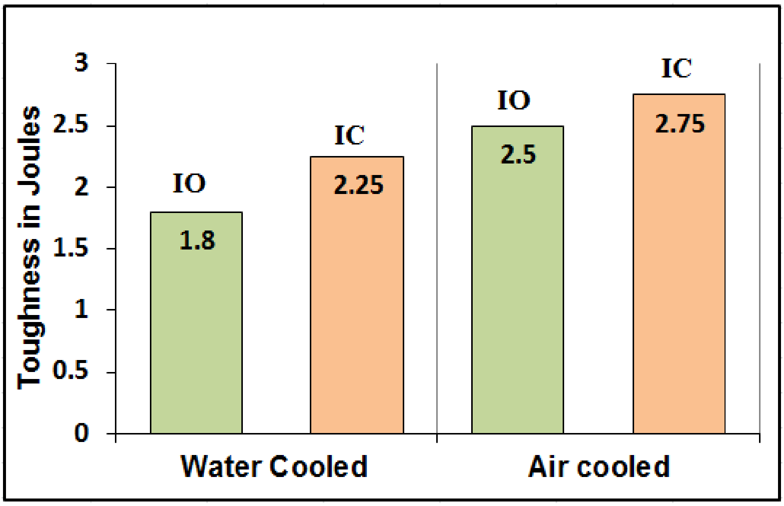



Fig. 9. Impact Strength (Toughness)-bar chart

## IV. CONCLUSION

The effect of different cooling rates during the solidification of the A380 aluminium alloy was examined. The following conclusions can be made:

- The short freezing (within 11.5 seconds) occurs in water-cooled casting compared to air-cooled (41.5 seconds) casting.
- Well refined eutectic silicon scripts are seen in water-cooled casting compared to air-cooled counterpart.
- Due to immediate chilling effect, fine eutectic silicon exists in the surface region when compared to core region in both air and water-cooled castings; this disparity is unavoidable in bulk castings.
- There is a disparity in the properties between the surface and core due to the variation in the grain size.
- Ultimate tensile, compressive strengths are considerably improved for the water-cooled casting compared to the air-cooled casting.
- The increased cooling rate (short freezing) results in the reduction of toughness.

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