

The influence of different casting method on solidification time and mechanical properties of AL- Sn castings

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Abstract

Solidification time is one of the very important parameters used for assessing the properties of the material. Aluminum casting alloys with tin as the major alloying elements are the most important commercial casting alloys because of their superior casting characteristics. This paper presents influence of different casting method on solidification time and mechanical properties of Al-(20%-40%) Sn alloys against both the molding conditions and tin content. Experimental investigation is carried out to measure the solidification time in cylindrical parts by using sand and die casting methods. The results showed different cooling rates and solidification times can produce substantial variation in the resulting structure and properties. However, decrease of both the ultimate tensile strength and the hardness is obtained by the increase of the tin content. For instance, die casting, which uses metal molds, has faster cooling and produces higher-strength castings than sand casting, which uses a more insulating mold material.

Keywords: Solidification time, die, sand, AL-Sn alloy, properties.

1. Introduction

Aluminum is one of the most versatile of the common foundry metals and the ratio of cast to wrought aluminum alloy products is increasing primarily because of the larger amounts of castings being used for automotive applications. A wide range of cast aluminum alloys is available for commercial use. Aluminium has a low modulus of elasticity and apart from indium, lead has the lowest modulus of elasticity of all the soft phases alloying with aluminium^[1]. The most commonly used processes are sand casting, permanent mould casting, cold chamber and hot chamber pressure die casting. Sand moulds are fed with molten metal by gravity^[2]. The amount of heat that must be removed from a casting to cause it to solidify is directly proportional to the amount of superheating and the amount of metal in the casting, or the casting volume. Conversely, the ability to remove heat from a casting is directly related to the amount of exposed surface area through which the heat can be extracted and the insulating value of the mold^[2,3].

During casting heat transfer occurs from the hot liquid metal to the cooled mold and the temperature decreases from that of the cast to the surrounding temperature. The process involves three successive stages: the cooling of the liquid metal, the solidification and finally the cooling of the solid metal. The process of solidification, the change of liquid to solid metal after pouring into the mold, is the defining event in the life cycle of a casting^[4]. The times involved in this activity may be as short as seconds or as long as hours depending upon the casting process and the size of the casting, the chemical composition of the metal being cast, the manner in which solidification occurs, and the subsequent solid state treatment determines the ultimate microstructure and therefore properties (mechanical and physical) of the casting^[5]. Cooling Rate can be an indication of material quality. Areas of the casting that cool rapidly generally have a more favorable grain structure, with less deposition of partially soluble compounds at the grain boundaries. Therefore, these areas tend to have better material properties such as strength, elongation and hardness. Those areas of the casting that cool more slowly generally tend to have poorer material properties^[6,7]. It is the duty of the metal casting

engineer to control the solidification event to the best of ability so that the microstructure of the final product can be controlled to optimize the properties desired. Dendrite cell size, which is controlled by solidification rate, is an important indicator of the mechanical properties of aluminum casting alloys^[8]. The ultimate physical and mechanical properties of the cast metal will depend upon both intrinsic factors (chemical composition, cooling rate during solidification and heat and mechanical treatment after solidification) and extrinsic factors (metal cleanliness, additives for microstructure control, casting design, riser and gating design, solidification rate control, and temperature control subsequent to solidification) present in each casting event and in the processing events subsequent to casting^[8,9].

2. Heat transfer and solidification in insulating molds

2.1 Chvorinov's rule

At some time, t , after pouring a pure metal into an insulating mold (sand or ceramic) at some pouring temperature T_p , the temperature along a line perpendicular to the mold-metal interface would be expected to look like the figure (1) below:

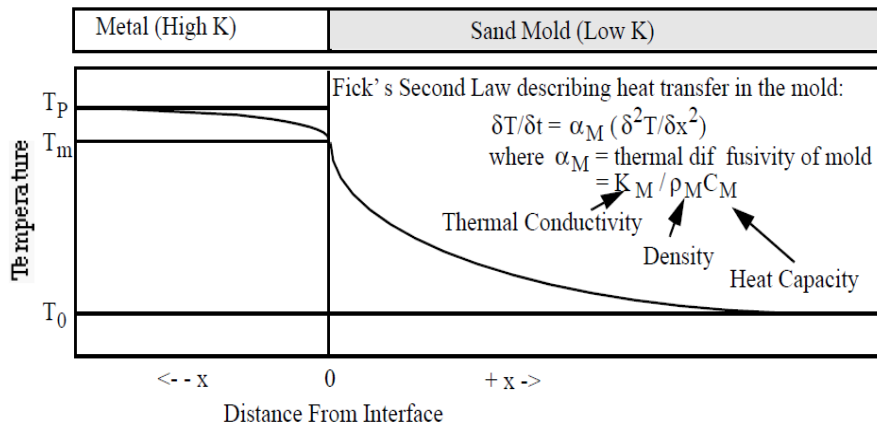


Fig.1: The temperature along a line perpendicular to the mold-metal interface

In this situation, the high thermal conductivity of the metal results in the temperature of the metal at the interface dropping to T_m instantly upon pouring and staying there until solidification is complete. of course, intimate contact between the metal and mold means that the mold at the interface will also remain at T_m until solidification is complete^[10,11]. The solution to the above equation subject to the boundary conditions that $T = T_m$ at $x = 0$ and $T = T_0$ at $x = \infty$ for small t gives:

$$T(x, t) = T_0 + (T_m - T_0) \left\{ 1 - \operatorname{erf} \left[\frac{x}{2\sqrt{\alpha_M t}} \right] \right\} \quad \text{eq.(1)}$$

This equation can be used to predict the solidification time, t_s . The flux of heat at the interface at time t is given by:

$$J = -KM \left(\frac{dT}{dx} \right) \Big|_{x=0} \quad \text{eq.(2)}$$

$$\frac{dT}{dx} \Big|_{x=0} = (T_m - T_0) \frac{d}{dx} \left[1 - \operatorname{erf} \left(\frac{x}{2\sqrt{\alpha_M t}} \right) \right] \Big|_{x=0} \quad \text{eq.(3)}$$

Expanding the erf function in the form:

$$\operatorname{erf}(u) = \frac{2}{\sqrt{\pi}} \left(u - \frac{u^3}{3.1!} + \frac{u^5}{5.2!} - \frac{u^7}{7.3!} + \dots \right)$$

and differentiating gives at $x = 0$, the interface,

$$J = \frac{K_M(T_m - T_o)}{\sqrt{\pi\alpha_M t}} \quad \text{eq.(4)}$$

The total heat, Q , through the interface of area A :(the total surface area of the casting) up to the time t , is given by:

$$Q = A \int_0^t J dt = \frac{2AK_M(T_m - T_o)}{\sqrt{\pi\alpha_M}} t^{0.5} \quad \text{eq.(5)}$$

The total heat liberated before solidification is a sum of the superheat, Q_S , and latent heat of solidification, Q_F where:

$$Q_F = \rho_{Metal} \Delta H_F V_{Metal}$$

$$Q_S = \rho_{Metal} V_{Metal} (T_P - T_m) C_{Metal}$$

Where T_P is the pouring temperature. The time necessary for this amount of heat to pass through the interface would correspond to the solidification time, t_S ,^[10,11].

$$Q_S + Q_F = \frac{2AK_M(T_m - T_o)}{\sqrt{\pi\alpha_M}} t_S^{0.5} \quad \text{eq.(6)}$$

And therefore:

$$t_S = \frac{\pi\alpha_M \rho_{Metal}^2 + V_{Metal}^2 [\Delta H_F + C_{Metal} (T_P - T_m)]^2}{4A^2 K_M^2 (T_m - T_o)^2} \quad \text{eq.(7)}$$

For a given metal and mold poured at a temperature T_P we can separate a mold constant B_S and the V/A ratio to give Chvorinov's rule,

$$t_S = B_S \left(\frac{V}{A} \right)^2 \quad \text{eq.(8)}$$

The constant needed to utilize Chvorinov's equation for a variety of materials are given below Chvorinov's rule: states that the total solidification time^[12,13]. The total solidification time is the time from pouring to the completion of solidification; V is the volume of the casting; A is the surface area; and B is the mold constant, which depends on the characteristics of the metal being cast (its density, heat capacity, and heat of fusion), the mold material (its density, thermal conductivity, and heat capacity), the mold thickness, and the amount of superheat. A thermal arrest is the plateau in the cooling curve that occurs during the solidification of a material with a fixed melting point. While the material is at this temperature, the heat being removed from the mold generated during the solidification process and does not require a decrease in the material's temperature. Chvorinov's rule can be used to ensure that the casting will solidify before the riser. This is necessary if the liquid within the riser is to effectively feed the casting to compensate for solidification shrinkage^[12,13].

2.2 Heat transfer and solidification in permanent molds

Heat transfer between liquid metal and a permanent mold can also be described mathematically in much the same way as was done for heat transfer in insulating molds. The major difference here is that the mold material has a much larger thermal conductivity than sand, and so the solidification will be

much more rapid. In the insulating mold the rate of transfer in the sand was the rate limiting step. In permanent molds the rate limiting step is at the interface between the metal and mold, where heat is transferred between the solidifying metal and the permanent mold, a mold which is usually coated with a mold wash or may quickly develop an air gap. The parameter which defines the transfer of heat between metal and mold in these cases is called the heat transfer coefficient, h . The model describing this event is illustrated below^[5,10].

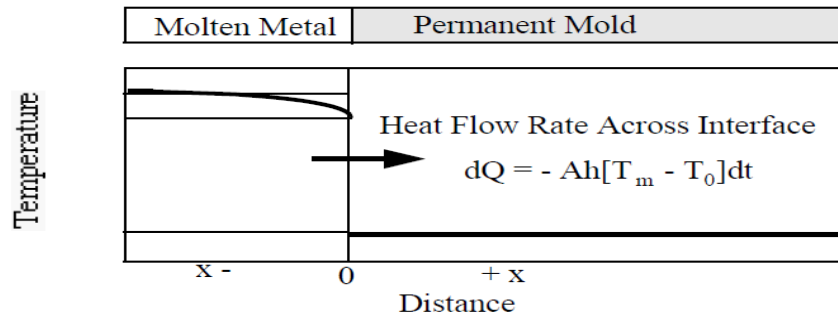


Fig.2: The interface between the metal and mold.

Notice in this schematic that the temperature drops discontinuously at the mold-casting interface. Heat flow within the casting and in the mold is very rapid (high thermal conductivity) compared to the relatively slow transfer across the interface. Thus the rate of heat removal and therefore solidification rate depends on the heat transfer coefficient, h , across the interface. The total heat flow in time t is then given by integrating the above expression, giving:

$$Q = -Ah(T_m - T_o)t \quad eq.(9)$$

and therefore for the solidification time, t_s :

$$Q_s = -Ah(T_m - T_o)t_s \quad eq.(10)$$

Using the relationships for latent heat and superheat given earlier, and solving for t_s gives:

$$t_s = \frac{\rho_{Metal} [\Delta H_F + C_{Metal} (T_p - T_m)] \left(\frac{V_{Metal}}{A_{Metal}} \right)}{h(T_m - T_o)} \quad eq.(11)$$

Writing an expression which is a similar to Chvorinov gives:

$$t_s = B_S(V/A) \quad eq.(12)$$

Where B_S is a mold constant and V/A is the modulus of the casting. It should be noted that, as opposed to solidification in a sand mold in which t_s varies as the square of the casting modulus, solidification in a permanent mold varies linearly with the casting modulus^[12,13and14].

Table (1): The constants needed to utilize Chvorinov's equation for a variety of materials.

| | Thermal Conduct. | Density | Specific Heat | Heat of Fusion | Melt Temp | Expansion Coeff. (68F) | Solidif. Volume Change |
|------------------|--|--|---|-------------------------------------|---------------------|--|------------------------|
| Material | K $W_m^{-1} \text{ } ^\circ C^{-1}$ | ρ $g \text{ cm}^{-3}$ ($mg \text{ cm}^{-3}$ $^\circ C^{-1}$) | C $J \text{ kg}^{-1} \text{ } ^\circ C^{-1}$ | ΔH_F $J \text{ kg}^{-1}$ | T_m $^\circ C$ | α $10^{-6} \text{ } ^\circ C^{-1}$ | % |
| Sand (SiO_2) | 1.5 | 2.32(bulk) 1.6 (Mold) | 1117 | | | 22.2 | |
| Al (liq) | 94.03 | 2.385 9-280 | 1080 | 395995 | 660 | | -6.5 |
| Al (sol) 20C | 238 | 2.7 | 917 | | | 23.9 | |
| Fe (liq) | | 7.015 (-883) | 795 | 272090 | 1536 | | -3.5 |
| Fe (sol) 20C | 78.2 | 7.87 | 456 | | | 11.7 | |
| Cu (Liq) | 165.6 | 8.0 (-0.801) | 495 | 211812 | 1085 | | -4.2 |
| Cu(Sol)20C | 397 | 8.96 | 386 | | | 16.5 | |
| Notes | W = Watts m = meter | mg = milli-grams | J = Joules kg = kilo-gram | | | Assume Temp Independent | |

3. EXPERIMENTAL PROCEDURE

3.1 Preparation of sand dies

3.1.1 Essential moulding equipment

1. A cylindrical solid pattern with diameter 32 mm and 85 mm height.
2. Moulding boxes, known as flasks. The best of these are made of cast iron, or welded out of steel, but satisfactory boxes have been made out of wood for many hundreds of years.
3. Parting powder. This prevents die sand in the two sides of the mould from sticking together. Brick dust powdered and sieved fine is excellent for this purpose. Fine chalk or talc is used to prevent die sand from sticking to the wooden pattern.
4. Sand moulding tools. To improvise these out of old knives, spoons or strips of steel, will need to make a wooden rammer and some wooden dowels or short pieces of pipe to form runners and risers. A strong piece of wire is used to vent die mould.
5. To recondition the sand will need a sieve.

3.1.2 Making solid casting

The sequence of operations to make a simple, solid casting:

1. The drag is inverted and placed face down on the turnover board. After the board is dusted with parting powder it is covered in facing sand which is pressed in place and then covered with backing sand (floor sand). This is rammed into place, and then more sand is added, rammed.
2. The drag is turned right way up. The cylindrical wood pattern with 32 mm diameter and long 85 mm is placed on the smooth surface, and parting sand dusted on. The runner tube is held in place. Facing sand is placed over the pattern and around the dowels. Then backing sand is rammed in place as described above.

3. The mould is parted (cope lifted off the drag) and the pattern removed. The gate or sprue system, which conducts the molten metal from the runner tube into the mould cavity, is cut in the sand. Both sides of the mould are vented with wire venting rods, the edges of the mould are made good, any fallen sand removed, and the mould put together.
4. Finally the cope is clamped to the drag
5. The Al, Al-20Sn and Al-40Sn alloys were prepared from commercial pure aluminium with appropriate addition of 99.99 wt. % pure Sn and Cu alloys. All compositions in this paper are given in wt%. The melt was prepared in a graphite clay crucible in electric resistance furnace model (SX 5-12). The furnace temperature was gradually increased and held 200°C above critical temperature (T_c). The melt was stirred, and it was homogenized by holding for a sufficient length of time and then poured into sand cavity of mold.
6. The mould is filled with molten metal and recorded the time of solidification.

3.1.3 Calculation solidification time of sand casting

Table (2) represents values of solidification time for alloys in sand casting, using the equation (7) for solidification time in sand casting and constants given in table (1).

Table (2): The values solidification time of alloys in sand casting

| Alloys | Solidification time Experimental(Sec) | Solidification time Theoretical(Sec) |
|----------|---------------------------------------|--------------------------------------|
| AL-20%Sn | 105.88 | 83 |
| AL-40%Sn | 111.33 | 91 |

3.2 Preparation the die casting

The basic steps of die casting are:

1. The cylindrical steel mold (with diameter 30 mm and 80mm height) is pre-heated up to 200C° before the metal is poured into die the cavity.
2. Cavity surface is coated with a thin layer of heat resistance material such as talc.
3. Pouring the molten metal in the die.
4. Metal solidification.
5. Casting is removed from the mold.

3.2.1 Calculation solidification time in die casting

The table (3) represents values of solidification time for alloys in die casting, using the equation (11) for solidification time in die casting and constants given in table (1).

Table (3): The values solidification time of alloys in die casting

| Alloys | Solidification time Experimental(Sec) | Solidification time Theoretical(Sec) |
|----------|---------------------------------------|--------------------------------------|
| AL-20%Sn | 2.5 | 1.77 |
| AL-40%Sn | 2.88 | 1.98 |

3.3 The Preparation of specimens of microscopical examination

In preparing a specimen for microscopical examination it is first necessary to produce in it a surface which appears perfectly flat and scratch free when viewed with the aid of a microscope. This

involves first grinding the surface flat, and then polishing it to remove the marks left by grinding. The polishing process causes a very thin layer of amorphous metal to be burnished over the surface of the specimen, thus hiding the crystal structure. In order to reveal its crystal structure the specimen is 'etched' in a suitable reagent. This etching reagent dissolves the 'flowed' or amorphous layer of metal.

Aluminum and its alloys are soft and easily scratched or distorted during preparation. For cutting specimens, sharp saw-blades should be used with light pressure to avoid local overheating. Specimens may be ground on emery papers by the usual methods, but the papers should preferably have been already well used, and lubricated. Silicon carbide papers (230, 320, 400, 600, and 1000 grit) which can be well washed with water are preferred for harder alloys, the essential point being to avoid the embedding of abrasive particles in the metal. For pure soft aluminium, a high viscosity paraffin is needed to avoid this. Polishing is carried out in two stages: initial polishing with fine-alumina, proprietary metal polish, or diamond, and final polishing with fine alumina using a slowly rotating wheel. It is essential to use properly graded abrasives and it is preferable to use distilled water only.

Etching the specimen, before being etched the specimen must be absolutely clean; otherwise it will undoubtedly stain during etching. Nearly every case of failure in etching can be traced to inadequate cleaning of the specimen so that a film of grease still remains. The specimen should first be washed free of any adhering polishing compound. The time required for etching varies with different alloys and etching reagents. Some alloys can be etched sufficiently in a few seconds, whilst aluminum and its alloys used Keller's reagent etch by immersion for 10-20 seconds. After being etched the specimen is washed in running water.

4. RESULTS AND DISCUSSIONS

4.1 Study of microstructure

In casting a homogeneous single phase liquid is cooled below the liquidus line, it transforms into two liquids, namely aluminium rich and tin rich. The minor 'Sn' rich phase segregates out. If the homogeneous single Al-Sn liquid phase is rapidly cooled, then the minor phase is dispersed uniformly in aluminium rich matrix. The microstructure of the alloys was investigated using optical microscope. Figure 3 shows the microstructure of AL-20% Sn . Here tin is distributed in aluminium matrix as a separate phase in form of reticular (network) structure along the edges of aluminium grains. This result is consistent with the previous observations by Varga Bela (Figure(4))^[15]. The 1% cu addition when made does not affect the structure, the copper being predominantly in solution in the aluminum matrix. From the optical micrographs for AL-40% Sn shown in figure (5) it can seem that the reticular tin structure. This type of structure consist of irregular islands of tin interconnected along trigonal aluminum grain boundaries to form a three dimensional net of tin throughout aluminum matrix.

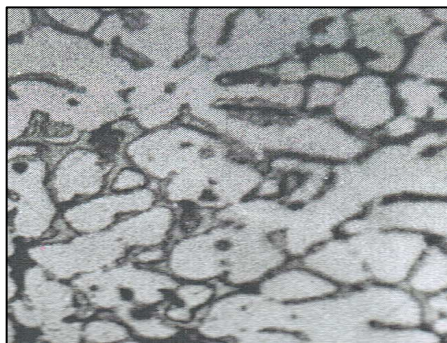


Fig.3: Images (optical microscope) showing reticular tin structure in Al -20%Sn casting alloy , 250 x .

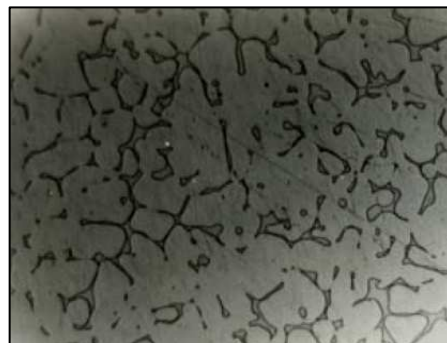


Fig.4: Schematic of the microstructure chill-cast Al-Sn 20 % alloy by Varga Bela,100x^[21]

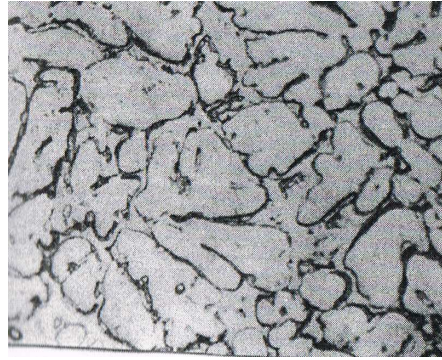


Fig.5: Images (optical microscope) showing reticular tin structure in Al -20%Sn casting alloy , 250 x .

4.2 Mechanical properties.

Results of the mechanical tests are presented in figure (6) and figure (7). The figures show the effect of tin content on the compressive strength and elastic modulus of Al-Sn casting alloys. It can be noticed that the increase of tin content from 20% to 40% gives a slightly decrease in the compressive strength and elastic modulus. These results are consistent with the previous observations by Mattia^[16].

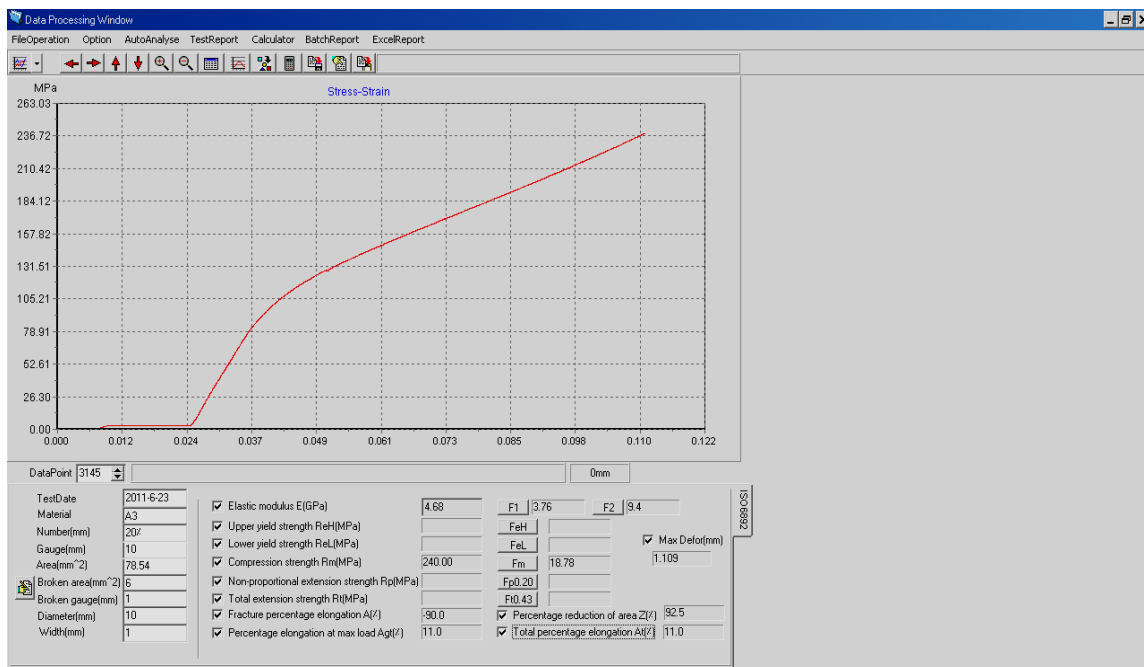


Fig.6: Effect of tin content on the compressive strength and elastic modulus. of Al-20%Sn casting alloy.

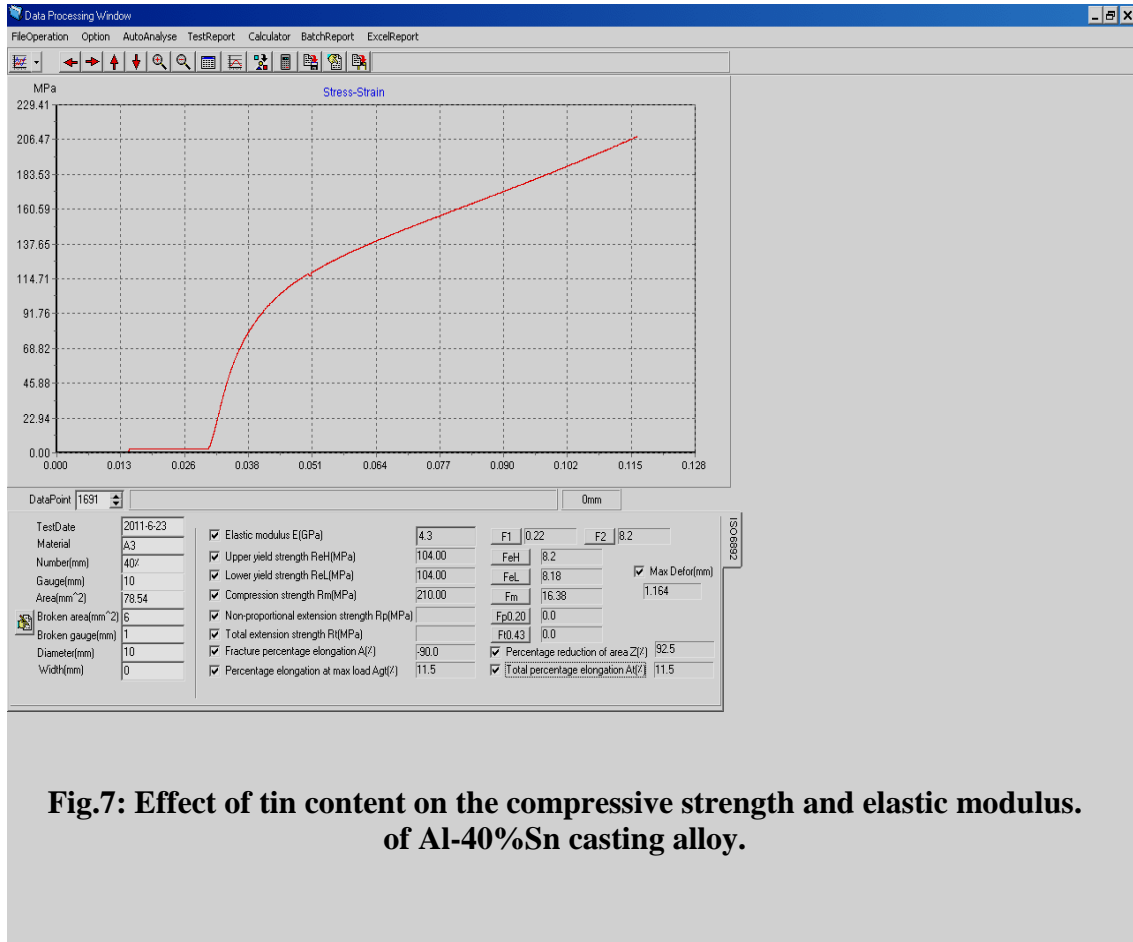


Fig.7: Effect of tin content on the compressive strength and elastic modulus of Al-40%Sn casting alloy.

4.3 Solidification time

The experimental and theoretical results of this investigation indicate that the solidification time of Aluminum-%Sn alloys in sand casting is always greater than the solidification time of Aluminum-%Sn alloys in die casting. The major difference here is that the mold material has a much larger thermal conductivity than sand, and so the solidification will be much more rapid. In the insulating mold (sand mold) the rate of transfer in the sand was the rate limiting step. In permanent molds the rate limiting step is at the interface between the metal and mold, where heat is transferred between the solidifying metal and the permanent mold. Also presence difference between theoretical and experimental value of solidification time, this difference may be because the sands with high moisture contents extract heat faster than sands with low moisture, then lead up to difference between theoretical and experimental value of solidification time.

The experimental and theoretical value of solidification time for aluminum-20%Sn alloy in sand casting is 105.88 sec and 83 sec respectively. Also the solidification time of Aluminum-20%Sn alloy in die is 2.5 sec and 1.77 sec respectively. While the experimental and theoretical value of solidification time for aluminum-40%Sn alloy in sand casting is 111.33 sec and 91 sec respectively. While the solidification time of the same alloy is 2.88 sec and 1.98 sec respectively, this is consistent with the previous observations for Abdel-Jaber and coworkers^[17].

5. CONCLUSIONS

1. In microstructure of Al -20%Sn casting alloy the tin is distributed in aluminium matrix as a separate phase in form of reticular (network) structure along the edges of aluminium grains.
2. The microstructure of Al-40%Sn casting alloy showing reticular tin structure in matrix of Aluminum.
3. Different cooling rates and solidification times can produce substantial variation in the resulting structure and properties. For instance, die casting, which uses metal moulds, has faster cooling and produces higher-strength castings than sand casting, which uses a more insulating mould material.
4. The solidification time of Aluminum-%Sn alloys in sand casting is always greater than the solidification time of Aluminum-%Sn alloys in die casting.
5. The increase of tin content from 20% to 40% gives a slightly decrease in the compressive strength and elastic modulus.

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Table (4) of Abbreviations

| Abbreviate | Meaning |
|--------------|-------------------------------------|
| T_m | Melting temperature |
| T_P | Pouring temperature |
| T_o | Mould temperature |
| J | The flux of heat at the interface |
| α_M | Thermal diffusivity of mold |
| K | Thermal conductivity |
| ρ | Density |
| C | Heat capacity |
| erf | Error function |
| Q | Total heat |
| A | e total surface area of the casting |
| Q_F | The latent heat of solidification |
| Q_S | Superheat |
| t_S | Solidification time |
| h | Heat transfer coefficient |
| B_S | Mold constant |
| ΔH_F | Heat of fusion |
| V | Volume of casting |