EFFECT OF PROCESS VARIABLES ON STRUCTURE AND PROPERTIES OF ALUMINIUM–SILICON PISTON ALLOYS.

BY

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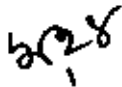## BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY, DHAKA, BANGLADESH.
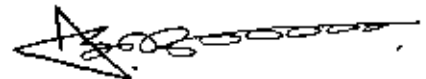
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DECLARATION

This is to confirm that this research work has been carried out by the author under the supervision of Dr. Md. Mohafizul Haque Professor and Head, Department of Metallurgical Engineering, BUET, Dhaka-1000, and it has not been submitted elsewhere for the award of any other degree or diploma.

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The undersigned examiners appointed by the Committee of Advanced Studies and Research (CASR) hereby recommend to the Department of Metallurgical Engineering of the Bangladesh University of Engineering and Technology, Dhaka-1000, the acceptance of the thesis entitled 'EFFECT OF PROCESS VARIABLES ON STRUCTURE AND PROPERTIES OF ALUMINIUM-SILICON PISTON ALLOYS' submitted by Md. Abdul Maleque, B.Sc. Engineering (Metallurgical), in partial fulfillment of the requirements for the degree of Master of Science in Engineering (Metallurgical).

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The majority of automotive pistons are cast in one of the group of low expansion aluminium-silicon eutectic alloys. The structure and properties of these alloys are very much dependent upon cooling rate, composition, modification and heat treatment operations. The effect of these variables have been investigated in this study. For this purpose, locally available automotive 'scrap pistons' were used as basic raw materials. Strontium master alloy (Al-14% Si-10% Sr) was used as a source of modifier. Natural gas fired crucible furnace was used for melting purpose.

The microstructures of the alloy both at modified and unmodified conditions have been studied in this investigation. Properties like UTS, percentage elongation, hardness and percentage porosity for rates of cooling were determined with and without strontium addition. Significant changes in structures were observed to occur specially in the primary and eutectic silicon phases. Modification exhibits the uniform, rounded and globular silicon instead of acicular type.

Full heat treatment (e.g., solution, ageing and precipitation treatments) has also shown a great influence on the structure and properties of aluminium-silicon piston alloy. The exceptional high tensile strength and hardness were attributed to the heat treatment condition with decrease in ductility. The heat treatment after modification produced the best combination of structure and properties of aluminium-silicon piston alloy. It is found that the sand cast material is more responsive to heat treatment than the chill cast material. The residual stress in the modified alloy is fully relieved due to thermal treatment.

Finally, attempts have been made to correlate the observed structures and properties obtained during the experiment.

CONTENTS

CHAPTER-01

1. INTRODUCTION

Aluminium-silicon alloys have the potential for high strength, excellent castability, good weldability, pressure tightness, thermal conductivity, strength at elevated temperature and corrosion resistance. They are therefore well suited for aerospace structural application, automobile industry, military application etc. The low expansion group of aluminium-silicon eutectic or near eutectic alloys are referred to as piston alloy. This alloy offers a design engineer, a potential replacement of cast iron for some applications specially for automotive pistons (both diesel and petrol engine), cylinder blocks, liners etc.. This alloy can also be used in compressors, reciprocating pumps, agricultural equipments and for other engine parts operated at elevated temperature. In recent years, it has further been established that their technological properties can be enhanced by varying the process variables like controlling cooling rate during solidification, adding modifiers, applying thermal treatment operations etc.

A review of the recent literature shows that a great deal of effort has been made to modify the alloy effectively. Earlier work for

modification of aluminium-silicon alloy was done with sodium or its salt and latter, it was carried out with strontium. One important feature of strontium mentioned in the literature is that its effect is similar to sodium but lasting longer than those of sodium. Therefore, the use of strontium should prove to have several advantages including the production and marketing of premodified ingots. However, if the alloy is heat treated, the strength and hardness are increased. Furthermore, this thermal treatment also relieves the internal residual stress of the casting, improving the service performance of the alloy.

The general theme of the present investigation was to observe effects of cooling rate, strontium modification and heat treatment operation on the structure and properties of this alloy.

However, Nowadays, most of the spare parts which belong to this low expansion group are being purchased from abroad with hard earned foreign currency. No research work has been carried out in Bangladesh to popularise the use of aluminium-silicon piston alloy with basic metallurgical variables. Another aim of the project was to find out specific conclusions and forward recommendations towards the technological use of this alloy for local automobile spare parts manufacturers.

CHAPTER-02

2. LITERATURE SURVEY

2.1. Introduction:

Aluminum is one of the most important non-ferrous metals today. After steels and cast irons, aluminum and its alloys constitute the biggest single group of metallic materials used by man. Out of 70 million tones per year, aluminium presently occupies the top position with over 18 million tones per annum[1]. Before the Second World War, it ranked fourth behind copper, zinc and lead in that order. In 1955 it jumped to first place and has since recorded the impressive growth rate of over eight percent per year for over 30 years now.

Recent developments in non-ferrous alloys have opened new possibilities in the field of aerospace technology and other related fields of materials in different developed countries. The aerospace technology, automobile industry, etc. mostly use the Alumiuium-Silicon alloys. During the past 10 years, a very successful effort has been made to improve and develop new aluminum alloys[2].

Basically, modern alloy development can be divided into four groups[3]:

(i) High strength alloys (e.g. Al-Si, Al-Zn-Mg-Cu)

(ii) Heat resistant alloys (e.g. Al-Fe-X)

(iii) Low density/high stiffness alloys (e.g. Al-Li-X)

(iv) Metal Matrix Composites or simply MMC.

High strength alloys are used in areas where a high strength/density ratio is required, e.g. in aerospace and transport technology. Development of an alloy of aluminium-silicon in the USA culminated in its successful use as an engine cylinder block in the Chevrolet Vega car in 1970[4]. Although aluminum alloy cylinder block casting had been used in the past, they usually incorporated a cylinder liner to provide the necessary wear resistance to the bore.

The following are the special features of aluminium-silicon alloys[5]:

(i) High thermal conductivity: About three times that of cast iron, which results in improved rates of heat transfer with regard to the cooling water and the lubrication systems.

(ii) Low coefficient of thermal expansion: Only slightly higher than that of cast iron.

(iii) Most of the physical and mechanical properties are retained

at operating temperature.

(iv) Enhance corrosion resistance.

(v) Adaptability to precision casting techniques (i.e. die casting)

(vi) Wear Resistance.

(vii) Reduced weight: density about 1/3 that of cast iron.

The last feature is particularly significant in the cumulative character of the results. As the engine becomes lighter, the supporting structure can be made lighter, thus decreasing the over all car weight. The result is that smaller engines may be used to give the same performance, which lead to more economical and lighter weight vehicles.

2.2. Aluminum-Silicon Alloys:

Many aluminium alloys contain some silicon, but the term Al-Si alloy usually refers to casting alloys with silicon from 5 to 22%. These high silicon alloys are characterized by their ease of casting, corrosion resistance, lightness and ease of welding. They cast well even in thin sections, but the strength decrease and they become more difficult to machine as the silicon increases. Aluminium and silicon form a simple eutectiferrous series with some

solubility at both ends- Fig. 1. At the aluminium-rich portion of the aluminium-silicon equilibrium diagram the solubility of silicon in aluminium decreases from 1.65% at eutectic temperature (577 C) to a negligible amount at room temperature[6]. A eutectic forming at about 12.0% silicon is largely responsible for the hardness of the cast aluminium-alloy. Two forms of silicon can exist in the alloys: (i) that resulting from precipitation from alpha-solid solution, and (ii) that produced by direct solidification from the eutectic melt. The two are crystallographically equivalent but differ in form and distribution. There are no intermetallic compound between aluminium and silicon.

Additions of copper increase the strength and improved the machinability and also add the property of age-hardening, but decrease corrosion and wear resistance. Slight additions of magnesium also give age-hardening by the formation of magnesium silicide (Mg_2Si). The high silicon provides good thermal conductivity and a low expansion factor, and are used for engine cylinders and pistons. Alloys having 7% silicon and 0.3% magnesium provide large needle shaped crystals which make the alloy brittle, but adding up to 0.04% sodium refines the crystals and improve the physical properties[7].
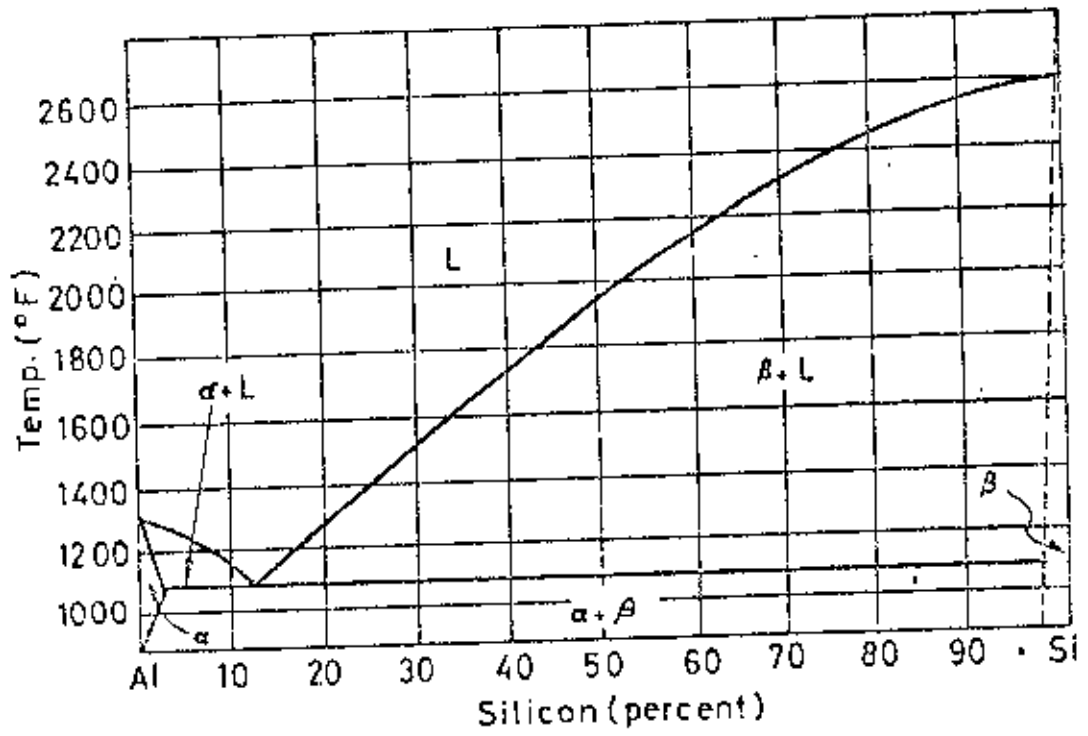
FIG. 1 EQUILIBRIUM DIAGRAM FOR ALUMINIUM-SILICON SYSTEM.

2.3. Solidification of Aluminum-Silicon Alloys:

Aluminium-Silicon is a metal/non metal system and it has been shown that the silicon particles in the solid aluminium-silicon alloys are interconnected[8]. The leading phase of aluminium-silicon eutectic is alpha-Al phase which normally nucleates first, followed immediately by nucleation of the silicon phase. The frontal growth of the solid is, therefore, the silicon phase, the edge of which is in contact with the liquid and surrounded on both sides by an aluminium-rich α-phase.

Following the theory of Day[9], the sequence of solidification in aluminium-silicon may be outlined. The eutectic point represents the fixed composition and temperature at which under equilibrium conditions, two solid phases separate from a single liquid. Solidification requires nucleation and growth of the solid phases and these in practice, require a driving force. This is supplied by under cooling, which represents a departure from the equilibrium (Fig.2).

Solidification begins at nucleating points in the melt and after nucleation, the solid aluminium and silicon phase grow rapidly side by side to form eutectic cells. The metal phase can grow easily in
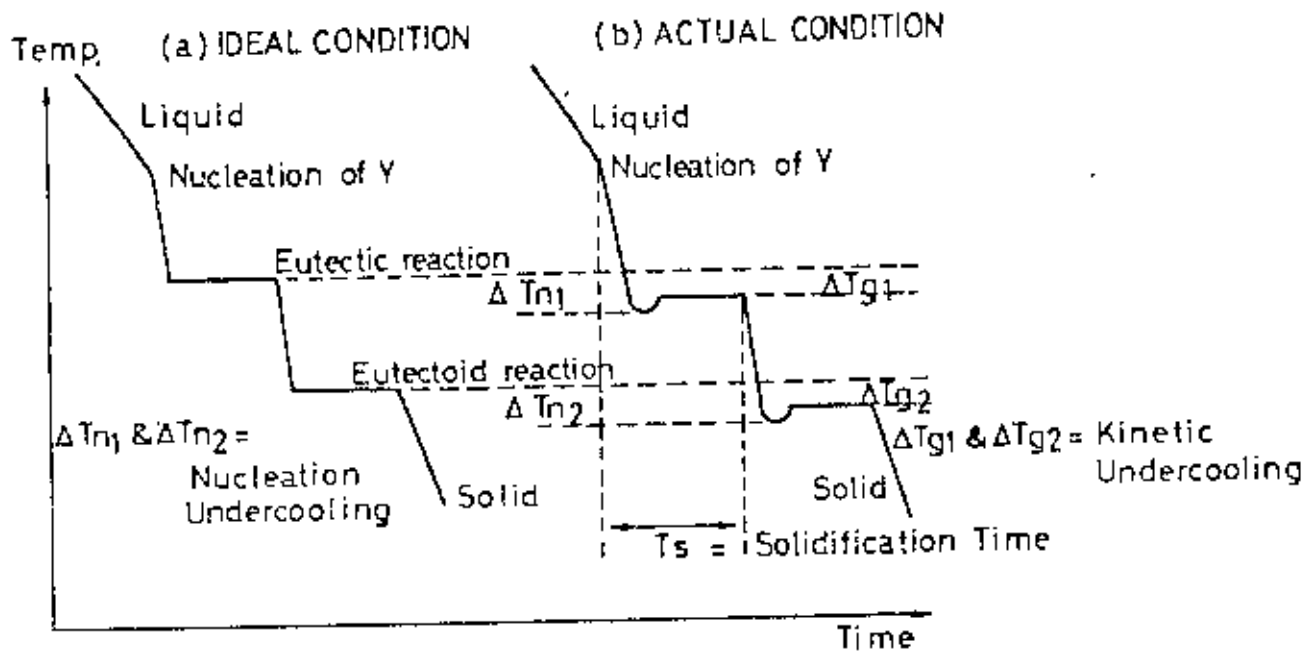
FIG. 2. A TYPICAL COOLING CURVE SHOWING NUCLEATION AND KINETIC UNDERCOOLING

various crystallographic directions and in addition, the solid/liquid interface is atomically rough so that atoms can attach themselves without difficulty; hence growth of aluminium is easy. The non-metal silicon, can grow only in a very limited number of crystallographic directions and its solid/liquid interface is atomically smooth. Growth of silicon is thus difficult[10]. The higher the cooling rate, the greater the degree of undercooling before the onset of nucleation. When nucleation does takes place, growth is faster and a finely branched silicon results.

2.3.1. Mechanism of Eutectic Solidification:

The mechanism of solidification of aluminium-silicon eutectic alloy has been exclusively explored in recent years and the theories have been reviewed by Chadwick[5]. However, at the eutectic point, the liquid alloy may be in equilibrium with two solids of different composition. The solution of the two phases must be accompanied by the redistribution of the two kinds of atoms which are present, and this redistribution must take place by diffusion in the liquid.

Two theories have been proposed for eutectic solidification. The first theory[2], is that nucleation and growth of a crystal of one phase so changes the local concentration in the liquid that it

becomes supersaturated with respect to the other phase. The second phase then nucleates and forms a crystal. Conditions then become reversed and the result is an alteration of the two phases. This may be described as the intermittent or alternate solidification of the two phases.

In the other theory[13] both phases crystallize simultaneously from the liquid. In the aluminium-silicon alloy, the aluminium forms a continuous matrix in which the silicon-rich phase is embedded. Intermittent crystallization can not occur when one of the solid phase is continuous and thus the second theory must therefore apply to the eutectic solidification of the aluminium-silicon system[14].

2.3.2. Nucleation and Growth:

Since solidification is a process of nucleation and growth, anything that influences the solidification process must influence the process of nucleation or the process of growth or both. The nucleation of eutectic represents a critical stage during freezing of an alloy and this starts from a number of potential nuclei and proceeds by growth to give eutectic cells.

It is generally agreed that crystal growth starts in the molten alloy by means of heterogeneous nucleation on some preferred site or substrate that lowers the surface energy which is essential for nucleation. Most commercial metals contain a sufficient number and variety of insoluble impurities for nucleation to occur. If the number of effective nuclei is insufficient for a given purpose, nucleating agents (nucleation catalysts) may be added to the melt.

In the case of pure metals, once nucleation has occurred crystal growth begins and the structures that develop can be related to the growth conditions, in particular to the undercooling. For growth to occur, more atom must join the solid than leave it and for this to happen, the temperature of the interface must be slightly below the equilibrium freezing temperature. This means that some undercooling must exist if the growth is to advance.

2.3.3. Factors Affecting Nucleation and Growth Processes:

The factors which affect nucleation and growth processes are as follows[16]:

2.3.3.1. Cooling Rate:

If the cooling rate is increased, the amount of undercooling is then greater which again increases the number of nuclei in the melt. The more undercooling, the more extensive is the nucleation and the smaller the final size of crystal or grain.

The cooling rate of a casting can be changed by varying the pouring temperature and section thickness. Higher pouring temperature gives more slow cooling of the casting throughout the freezing range. Alternatively, in thin casting, the rate of cooling is higher than the thick casting having same pouring temperature. With lower cooling rates, the degree of under cooling is less and few nuclei are available for growth which eventually contributes to the formation of coarse and thick instead of fine crystals.

2.3.3.2. Nucleating Agents:

A nucleating agent is a substance which can be intentionally added to make effective substrate that facilitate the nucleation in the melt. The exact nature of a good nucleating agent for a specific metal is seldom known in advance and in practice, nucleating agents are found by a trial and error method. eutectic that is normally acicular may be changed to another form by altering the growth rate

and or by adding a specific impurity. If magnesium is added to aluminium-silicon eutectic or if the eutectic is chSwl cast, the needle becomes more fine. It is obvious that the number of silicon particles (eutectic cells) is greater after magnesium-addition than before and this means that more nucleation must have occurred in magnesium-added eutectic[16].

2.4. Theory, Practice and Modification of Aluminium-Silicon Alloys:

Aluminium-Silicon alloys have been known according to literature for about 138 years ago. Among the earliest records are those prepared by the two founders of the science and technology of the alloy, Wohler and Deville[17]. Their alloys are reported to have contained at least 10% silicon and were produced from Potassium Silicofluoride by reaction with aluminium. Until 1900, the addition of silicon to aluminium was considered to be detrimental and hence the aluminium-silicon alloys were not used. As early as 1891, however, Minet[18] recognized that an abnormal mode of crystallization could occur in the alloys of aluminium and silicon. This discovery received no attention, and it was not until 1920 that the commercial potentiality of these alloys was realized.

Thus, the use of aluminum-silicon alloys for the production of castings received a strong boost from that year when Pacz[19] added sodium or its salts to the molten alloy resulting structural modification during solidification and hence a considerable improvement in mechanical properties was obtained.

Further developments in modification took place in 1922 and 1923 with the introduction of the use of the alkali metals by Edward[20], et al. The main effect of Na, however, manifests itself during the growth of eutectic. In non-modified alloys the eutectic grows with silicon leading the crystallization, consequently forming continuous skeletons. In modified alloys, aluminium precedes the silicon and tends to envelop it. This enveloping action breaks up the silicon in many small crystals imbedded in the aluminium-matrix. It also makes necessary continuous renucleation of silicon by aluminium, therefore lowering the freezing point of the eutectic to the temperature at which aluminium nucleates silicon.

However, Curran[21] suggested an explanation in terms of the ternary Al-Si-Na system, and Otani[22] developed this theory to show how sodium played its parts in the production of the modified structure. It was proposed that, in the modified alloys, the modifying agent performs the function of a protector by retarding

the rate of coalescence and thus leads to the fine, modified structure.

The principle of the restriction of growth of a dispersed phase was described by Edwards and Archer[23], who assumed that, in the modified alloys, sodium separates as a discrete liquid phase just before solidification of the eutectic. This phase was considered to be a fine state of subdivision similar to that of colloid. It was further suggested that the fine sodium dispersion hindered crystallization of the silicon and to a lesser extent, that of the aluminium. The finer structures obtained in the eutectic of the modified alloys are accounted for partly by obstructing effect of the sodium globules and partly by the rapid formation of silicon nuclei in the under cooled liquid.

The modification treatment has been carried out exclusively with sodium, although its action is short lived as it rapidly vanishes with time. Thus, attempts have been made to replace sodium by other elements for modification of aluminium-silicon alloys. In 1966 Thiele and Dunkel[24] show that the effect of strontium on such alloys are similar and long-lasting than those of sodium. Other investigators [25-27] also claim that it is possible to produce almost permanent modification of these alloys by strontium. A comparative study has also been carried out by Haque[28] who reports

that better mechanical properties and finer structure were obtained when strontium was used for modification of aluminium-silicon casting alloy instead of sodium. Another study[29] has been made on the modification of the particle morphology of the silicon phase by the addition of strontium.

The use of strontium has also several advantages including the production and marketing of the premodified ingots. But the use of this metal is subject to certain limitations, and the strontium must be added according to vary precise criteria in order to be completely effective. Many Researchers[25,28,30] have found the problem with strontium recovery. The problem was due to the delay of dissolution of the strontium-master alloy in the melt. When strontium was added after melting the alloy and the melt was supper heated prior to teeming, metallurgical examination of the cast test pieces show some undissolved strontium particles.

Therefore, strontium master alloy should be added with the charge at the beginning of the melting and the incubation time including super heating temperature should be controlled precisely. The incubation time needed to modify the alloy satisfactorily is found to be about 15 minutes of which 5 minutes must be at the super-heating temperature of 750 C in order to effect adequate solution of the master alloy [30].

Figure 3 shows the pattern of the cooling curves obtained during solidification of LM-6 type alloy which contains various alloying and impurity elements. Each curve shows two arrests, first, the liquidus is caused by the nucleation of primary aluminium solid solution. The number of nuclei depends on the cooling rate and process variables, which latter determine the size of the as-cast primary dendrites. Once nucleation has started, the primary dendrites grow by deposition of further aluminium which cause recalescence.

The secondary arrest on the cooling curves is caused due to the eutectic solidification of the alloy. The eutectic temperature of the normal (untreated) alloy (Fig. 4b) was recorded as 577 C (curve C) which has lowered to 568 C (curve B) with the introduction of sodium and approached 569 C (curve A) when strontium was introduced into the alloy[31].

During growth of the eutectic cells, the liquid between the aluminium dendrites becomes progressively richer in solute elements, since they are rejected by both aluminium and silicon and these form complex phases which at lower temperatures nucleate on the eutectic already present. Growth of these constituents is slow and therefore, a coarse intermetallic network forms throughout the structure to complete the solidification sequence. It is
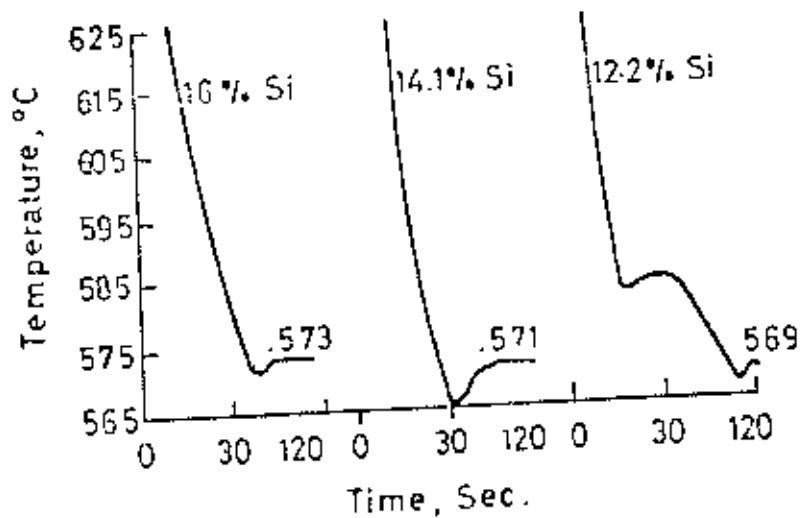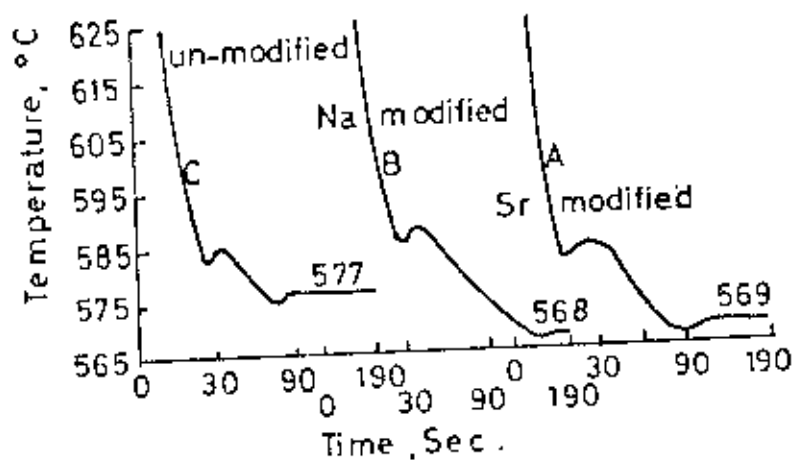
FIG. 3. EXPERIMENTAL COOLING CURVES FOR LM-6 ALLOY
(a) HIGH SILICON CONTENT (b) MODIFIED WITH MODIFIERS

suggested[31] that after solidification of the primary aluminium dendrites, the aluminium-silicon eutectic starts to freeze until the liquid becomes saturated with impurities (Fe, Mn) and then the intermetallic forms.

However, the basic differences between modified and nonmodified alloys is that in nonmodified alloys, the eutectic silicon once nucleated by aluminium, grows ahead of the advancing aluminium interface to form a continuous Si platelet network. Since both phases remain in contact with the liquid throughout the course of eutectic crystallization, growth is possible at the equilibrium temperature. In modified alloys, silicon is likewise nucleated by the aluminium but it does not grow ahead of the aluminium. The aluminium phase defines the crystallization front and grows around the silicon, isolating it from the liquid.

Figure 4 is a schematic sketch of the change of growth. This switch of leading phase for eutectic crystallization is the critical point of the modification process and the experimental evidence for it is overwhelming. The continuity of silicon particles through the aluminium, the interpenetration of silicon plates where two different orientations meet, the presence of aluminium rich liquid around the growing silicon needles as visible in the quenched
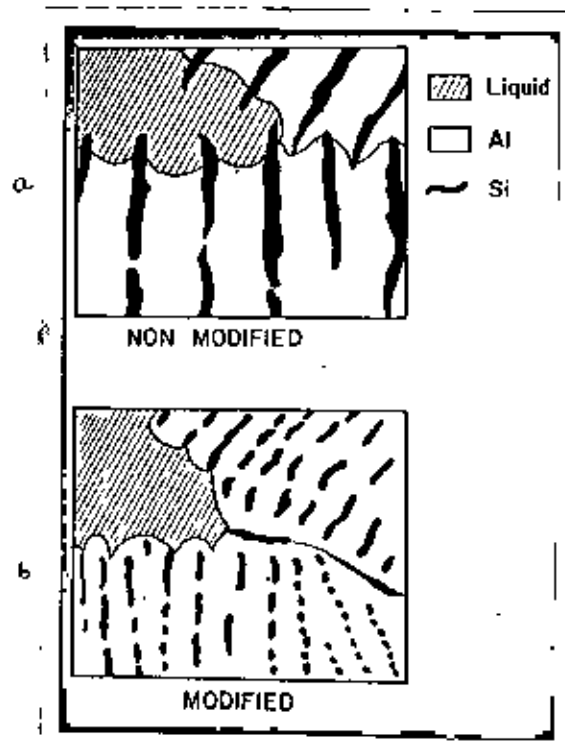
Fig.4. Schematic freezing of Al-Si eutectic; (a) unmodified: Si
crystals leading crystallization. Notice interpenitrating
Si crystals at grain boundary; (b) modified: Al loading
crystallization, notice boundary composed of aluminium with
silicon films forming from excess silicon iu residual
liquid.

alloys and the bush shape of eutectic silicon extacted from nonmodified alloys,[8,32] are some of the evidence for the silicon lead in nonmodified alloys. In the modified alloys the discontinuity of the silicon is proven by the better distribution of the eutectic colonies with aluminium at the boundaries, the presence at the grain boundaries of occasional silicon films arising from the excess silicon in the liquid, the globular appearance of the silicon when sectioned and the necessity of continuous ranucleation. Further support of this change can be obtained from the mechanical properties.

2.5. Factors influence Aluminium-Silicon Casting:

The melting and casting of Aluminium and its alloys are also affected by the following foreign elements[33].

2.5.1. Hydrogen and oxygen:

When melted in the air, aluminium alloys are oxidized and saturated with hydrogen. When the oxidation films on the surface attain a thickness of 0.2 mm, the rate of oxidation decreases sharply owing

to a low rate of oxidation- diffusion through the film. Hydrogen can be dissolved in Aluminium in an amount up to 3 cm^3/100 gm of the melt which indicates that these alloys are strongly liable to form gas blow holes and porosity in castings. Addition of alkali and alkali-earth metals increases the solubility of hydrogen in Aluminium.

2.5.2. Water Vapor:

Water vapors are the most harmful component of furnace gases for Aluminium. They react with Aluminium according to the following reaction:

$2Al+3H_2O = Al_2O_3 + 6H$, leads to contamination of the melt with Aluminium oxide and hydrogen.

2.5.3. Air Entrapments:

Air entrapment in pouring the metal into high moulds is prevented by using multi-step or slot type gating systems which additionally ensures a more favorable temperature distribution along the mould height.

2.5.4. Shrinkage Porosity:

The major factors which control the formation of shrinkage porosity in the cast alloys are solidification temperature intervals, temperature gradient in the freezing zone and growth morphology. The recent investigation[34] expressed in detail the importance of grain growth morphology upon porosity formation in case of long freezing range alloys. Al alloys are liable to form shrinkage porosity which can be prevented by arranging large volume of risers and chills or for more critical casting by letting the metal to solidify in compressed air.

2.6.Residual Stresses in Casting:

The internal residual stresses in the casting aries from the following sources[35]:

(i) Uneven cooling rates of various sections of the casting,

(ii) Resistance of the mould to normal solid contraction of the casting, and

(iii) During shaking of the casting from the mould, the internal stresses may be locked in the structure.

(iv) During welding or result from other fabrication operations.

The effect of residual stresses can be either beneficial or detrimental depending upon their magnitude, sign (tensile or compressive), and distribution with respect to the service induced stresses[36]. Castings are often given a thermal stress relieving treatment for removing objectionable stresses. Stress relieving is conducted at somewhat lower temperature for non-ferrous metals.

There are numerous examples of the use of such heat treatments to effect a reasonable degree of stress relief. One example is the work of Hill et al.[37] (1960) on aluminium alloys, where they have described an "up-quenching" technique. There may be greater certainty of a valid result with sub-resonant. This technique has emerged only recently as a possible method of stress relief[38] (Hebel, 1989). In this technique the casting is vibrated not on the peak of the frequency-amplitude curve, but low on the flank of the curve. Thus, although quality-control checks cannot be specified to asses the levels of retained stress in a part, process control can be specified and checked, and this will provide a reliable safeguard.

Stress relieving may also be accomplished wholly or partly by mechanical means [35]. But such methods are not common. viz.

(i) Casting surfaces are sometimes shot-pined for eliminating

surface tensile stresses and introducing surface compressive
stresses (to improve fatigue life).

(ii) Residual casting stresses are, re-distributed by stressing
beyond the yield point, e.g., overspeeding turbine wheels,
using autofrettage for prestressing large gun barrels.

For the last four decades, the sectioning (saw cutting) method has
been used extensively for measureing the residual stresses. The
studies conducted at Lehigh University by some researchers[39,40] have
made significant contributions to the understanding of the
magnitude and the distribution of the residual stress. Although the
sectioning method is one of the most reliable techniques for
residual stress measurement, it is destructive and the sectioning
procedure itself is very time consuming and costly.

Now-a-day, the semi-destructive blind hole-drilling strain gauge
method is applied for residual stress measurement. An experimental
investigation[30] of the residual stress was done by the blind hole-
drilling method and found that this method is much less time
consuming than the conventional sectioning (saw cutting) method.
Neutron diffraction is also a well established method for the
measurement of residual stresses inside metallic engineering
components.

2.7. Effect of Process Variables on Al-Si Alloys:

There are many process variables which affect the structure and mechanical properties of Al-Si alloys. The process variables may include the following:

(i)   Effect of alloying elements (i.e. compositions)

(ii) Effect of casting temperature

(iii) Effect of heat treatment .

2.7.1. Effect of Alloying Elements:

Chromium: Chromium additions are commonly made in low concentrations to room temperature aging and thermally unstable composition in which germination and grain growth are known to occur. Chromium typically forms the compound $CrAl_7$, which displays extremely limited solid-state solubility and is therefore useful in suppressing grain growth tendencies. Chromium improves corrosion resistance in certain alloys and increases quench sensitivity at higher concentrations[14].

Copper: The first and most widely used Aluminium alloys were those containing 4 to 10% copper. Most of the copper is present in solid solution in the Aluminium matrix, although some occurs in the

compounds, especially in association with nickel. The equilibrium solid solubility of copper in Aluminium falls from about 5.5 wt% at the liquidus to about 0.2 wt% at room temperature and this limits are probably approximately the same in the aluminium-silicon commercial alloy[42]. Copper substantially improves strength and hardness in the as-cast and heat treated conditions. Copper generally reduces resistance to general corrosion and in specific compositions and material conditions, stress corrosion susceptibility. Addition of copper also reduce hot tear resistance and decrease castability.

Alloys containing Copper and silicon with smaller amounts of other elements cover a wide range of mechanical properties[43], and they are useful for some of the specialized purposes. The Al-Cu-Si alloys have better casting characteristics than the Al-Cu alloys but are not so resistant to corrosion as the aluminium-silicon alloys. The Copper content provides strength and hardness, while the silicon content improves the casting qualities and increases the resistance to corrosion. The effect of copper on aluminium is substantially greater than that of other solution hardeners and this has been attributed[44] to the rather large difference in lattice parameter of the two constituent atoms.

Nickel: Nickel is mainly present in the form of a series of dark etching, relatively massive compounds; the etching response within a single phase can vary markedly, indicating that the phases are capable of existing over a range of composition. The etching behavior is also affected by the presence of copper, which can enter into compound formation with the nickel. Nickel is usually employed with copper to enhance elevated temperature properties. It also reduces the co-efficient of thermal expansion. Nickel, originally in amounts of 2-3%, has been a traditional alloying addition in low expansion alloys apparently because it was thought to improve mechanical properties at elevated temperatures. The evidence has been accumulated on the precise effect of nickel on the mechanical properties by R. A. Day et. al[45] in more details. Hanafee[46], found that, within the 0-2.5% range, nickel increased the hardness of a LM13 type alloy.The nickel element provides dispersed compounds in microstructure. The large volume of silicon that is present in structure can be swamped by any nickel effect.

Magnesium: Magnesium is mainly present as the Mg_2Ni complex compound, only a small amount going into the aluminium matrix or into the other compounds. Above the solubility limit, it appears as a coarse, primary constituent, typically in script form. In fully

heat treated alloy, it is present as a picture of coherent with the matrix and is not optically resolvable[41].

It is obvious from the result of the addition of magnesium, has definite effect on the aluminium-silicon alloy. The effect of magnesium, copper and nickel have been studied by R.F. Smart[10], based on about 10.5% silicon, in which each specimen contained different amount of the three elements. The effect of these elements in hardening the aluminium-silicon alloy have been shown in Fig.5. The magnesium is more powerful hardener than copper but, unlike the later, its effect is fully observed only after heat treatment. This is to be expected since, magnesium functions mainly as a precipitation hardener. The strengthening effect is not liner, the initial addition of 0.4% being most effective. The coarse, primary Mg_2Si has little beneficial effect on mechanical properties. The aluminium-silicon alloys stand highest on the list in corrosion resistance and has excellent casting characteristics, which are important in reproducing fine design details. When low electrical conductivity is necessary, an alloy containing 6% Mg, 1.5% Mn, and 1.5% Ni can be used.

Iron: Iron improves hot tear resistance and decrease the tendency for die sticking or soldering in die casting. Increases in iron
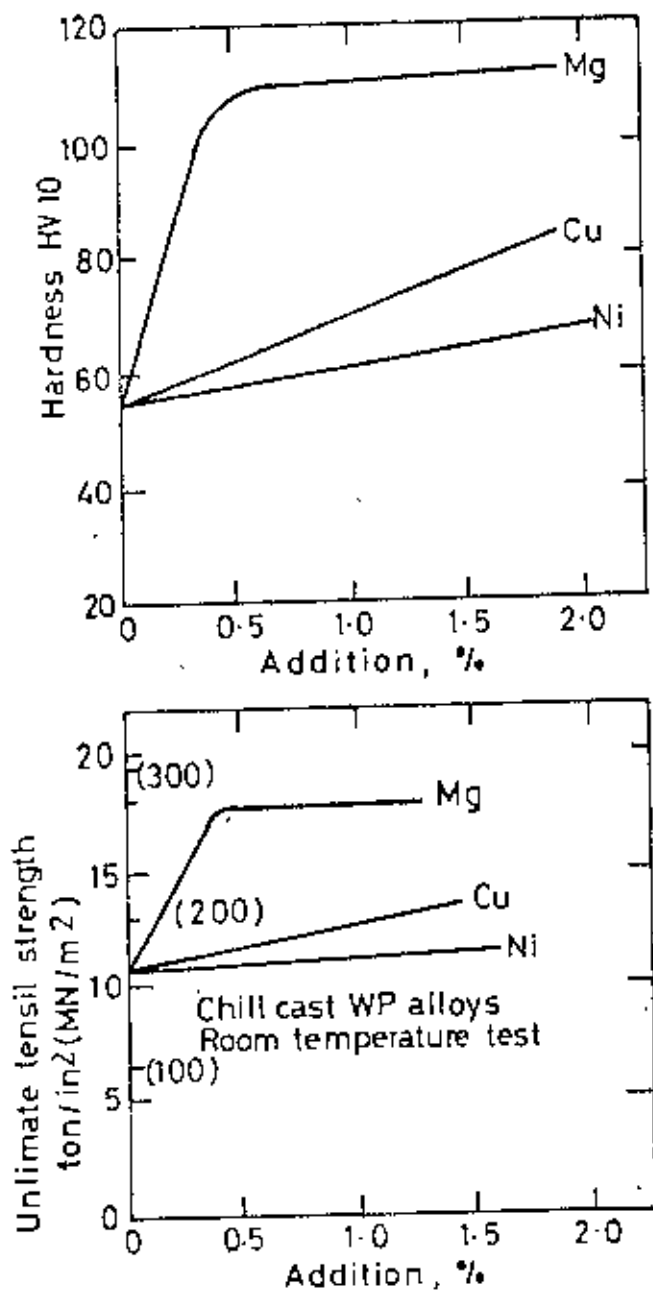
FIG.5. STRENGTHENING EFFECT OF ALLOYING ADDITIONS
ON ALUMINIUM - SILICON BASE.

content are, however, accompanied by substantially decreased ductility.The presence of iron leads to the formation of Al-Si-Fe compounds which tends to be acicular in shape[47].

Silicon: Outstanding effect of silicon in aluminium alloys is the improvement of casting characteristics. It improve fluidity, hot tear resistance and feeding characteristics silicon reduce specific gravity and co-efficient of thermal expansion. Silicon increases the strength and decreases the ductility of the matrix[47].

In some alloys the formation of Si containing compounds makes the alloys heat treatable which gives further improvements in mechanical properties. But such alloys have a low strength at elevated temperature and this has led to the introduction of magnesium and copper which allow the alloys to achieve the significant improvement by precipitation heat treatment and the use of Ni, Cr Mn etc. to improve hot strength[48].

Antimony: At concentration levels equal to or greater than 0.05%, antimony refines eutectic aluminiun-silicon phase to lamellar form in hypoeutectic compositions. The effectiveness of antimony in altering the eutectic structure depends on an absence of phosphorus and on an adequately rapid rate of solidification.

Antimony also reacts with either sodium or strontium to form coarse intermetallics with adverse effects on castability and eutectic structure[41].

Lead: Lead is commonly used in aluminium-silicon casting alloys at 0.1% (max.) for improved machinability.

Manganese: Manganese is normally considered an impurity in casting compositions. In the absence of work hardening, manganese offers no significant benefits in cast aluminium alloys. Some evidence exist, however, that a high volume fraction of $MnAl_6$ in alloys containing more than 0.5% manganese may beneficially influence internal casting soundness. Manganese can also be employed to alter response in chemical finishing and anodizing[41].

Zinc: Zinc has also been kept to low specification limits in most aluminium-silicon eutectic type alloy,. Economic considerations have led to recent investigations of the effect on mechanical properties of relaxing the limits of zinc. Day et al[45]. has shown that additions upto 0.5% give no significant deterioration in mechanical properties.

2.7.2. Effect of Casting Temperature:

Melt Temperature:

The maximum melt temperature, i.e., the highest temperature reached by the molten alloy during the melting or refining operations, is considered as an other important factor affecting melt quality. In general, it has been found that overheating of the melt is deleterious to the mechanical properties and grain size of aluminium casting alloys[49]. Cooling the melt down to a low pouring temperature may, in some alloys, restore partly or completely the properties of the casting.

Holding Time:

It is always desirable that the holding time, i.e., the time the alloy is kept in the molten state before pouring, be as short as possible[50]. In commercial foundry practice this can not be consistantly obtained, because of unforeseen delays in mould preparation, or similar operational shortcomings. It is essential, therefore, to know how such prolonged holding times, at various melt temperature levels, affect the properties of the castings.

Hurren[51] found that the effect of prolonged heating on tensile properties was only slight, but reported a greater influence on the resistance to repeated impact.

Pouring Temperature:

Most foundrymen are aware of the importance of the proper choice of strict control of the pouring temperature. It is accepted that the best one for most aluminium alloys is the lowest temperature at which the sound casting can be produced and that, usually, the mechanical properties can decrease with the increase of pouring temperature. There are numerous references on the effect of pouring temperature on the mechanical properties of aluminium casting alloys. In most cases, the decrease of mechanical properties with rising pouring temperature has been attributed to the increase in grain size.

Colton and LaVelle[52] do not believe that lower mechanical properties of castings are due to large grain size, and state that the decrease in strength and ductility is due to increased shrinkage and gas porosity caused by higher temperature. The large grain size, they say, is also caused by high temperature, but this is merely a concurrent phenomenon not the cause of poor properties. They found that test bars of equal soundness have equal properties, regardless of the grain size within a 10-15 fold range. To

overcome the effects of grain coarsening at higher temperatures, the use of more effective grain refiners has been recommended[53].

2.7.3. Effect of Heat Treatment:

The principal objectives of heat treatments are[54] :

i)   to homogenize the cast structure which is nonuniform because of selective solidification during freezing.

ii) to relieve stresses induced by cooling after casting, during quenching, welding or forming.

iii) to avoid the dimensional changes which might otherwise occur in service, especially for parts which operate at elevated temperatures with close tolerances.

iv) to remove the effects of cold work which the metal has received either during fabrication, as in cold rolling, or subsequently in forming.

v)   to produce specific mechanical properties, i.e., tempering in cold-worked and heat treated alloys.

The effect of heat treatment upon an Al-Si alloy depends on the following factors[55]:

(i) Silicon content

(ii) Degree of chilling in casting

(iii)Duration and temperature of heat treatment

(iv) Rate of cooling from the solution temperature

. (v) Degree of modification.

In most of the heat-treatable aluminium alloys, artificial aging produces a higher strength and lower elongation with very much higher yield strength than in the case of natural aging. The fatigue strength is not increased correspondingly and the notch fatigue strength may even be decreased.

If solution heat treatment is followed by artificial aging, some of the alloying elements are precipitated in the alloy, which further increases the strength and hardness. Prolonged artificial aging provides dimensional stability, but the strength and hardness pass through maximum values and drop, and at the same time the elongation may increase somewhat.

Controversial opinion exists with the effect of heat treatment on modified alloys. Modification alters the properties of the aluminium-silicon alloys containing magnesium and makes the alloys more responsible to heat treatment[41] and also gives more ductility after heat treatment. But it has also been reported by an another author that the modifiers (Na and Sr) have very little influence on the property of heat treated materials.

The strengthening role of different elements on aluminium-silicon eutectic alloys has recently been clarified[10,56]. The addition of magnesium to sand cast aluminium alloys with 5-11% silicon increases strength and hardness and decrease elongation as shown fig. 6. According to Bailey[57] at any ageing temperature or time, for both sand and chill casting, the ultimate tensile strength and yield strength increases directly and the percentage elongation as measured by "fit back" varies inversely with increase in magnesium concentration from 0.33 to 0.74 weight percent.

2.8.   Application of Al-Si Alloys:

Aluminium-Silicon alloys are the most widely used Al-casting alloys, primarily because of their excellent castibility. They find considerable application in marine equipment and hard ware because of high resistance to salt water and saline atmosphere. They are also used for decorative parts because of their resistance to natural environments and ability to reproduce detail. Although steel, titanium alloys and composites are to be considered along with aluminium and its alloys as primary materials of aircraft construction, 70-80% of the total structural weight of conventional aircraft, small and large, is provided by Al-alloys.

Aluminium-silicon   eutectic or near eutectic alloys are usually used for making pistons for all types of diesel and petrol engines,
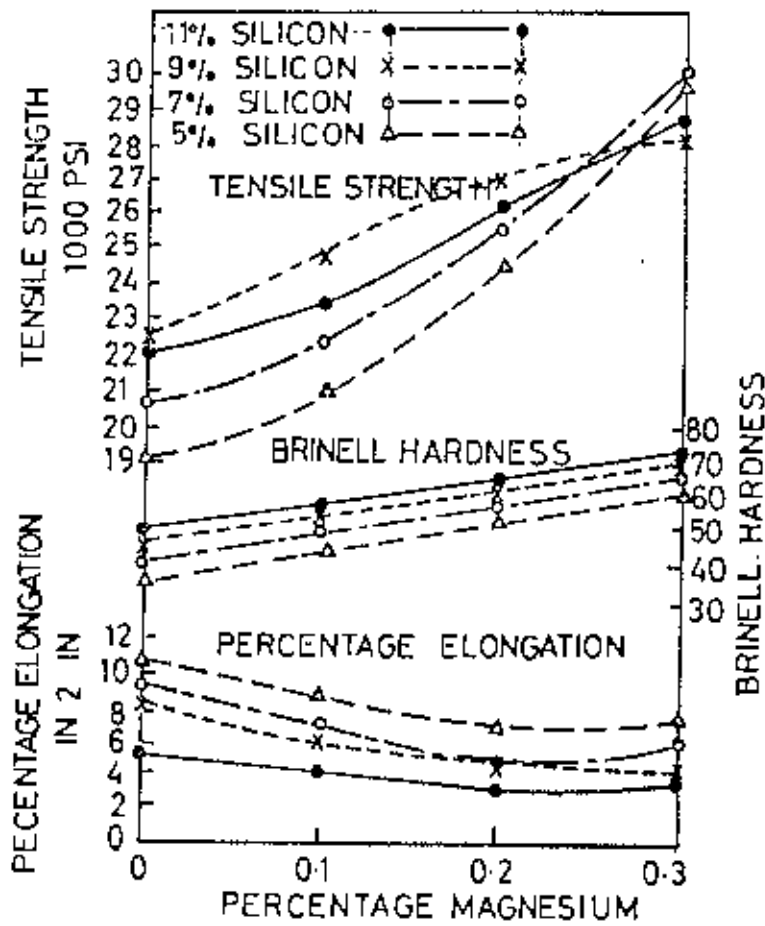
FIG. 6. EFFECT OF MAGNESIUM ON THE TENSILE PROPERTIES OF
FOUR AL-Si ALLOYS IN THE SOLUTION HEAT TREATED CONDITION

compressor, reciprocating pump, agricultural parts and for other engine parts operating at elevated temperatures. These alloys are also used in making liners, piston ring, cylinder blocks etc.

In view of the large requirements of aluminium for the aircraft industry, the later has taken strong initiative in sponsoring as well as undertaking research on applying Rapidly Solidification Process (RSP) to Al-alloys through the Powder Metallurgy (PM) route.

2.9. Limitations of Al-Si Alloys:

A major limitation common to Al-alloys thus far is their lack of thermal stability[1] i.e.,their loss of strength at a rapid rate between 100 and 200 C (375 and 475 K) due mainly to precipitate coarsening. Resistance to such coarsening can be increased through some transition metal additions. The low modiolus of elasticity is yet another deficiency of conventional Al-alloys. It is well known that worth while design pay-offs in airframes can result from even a slight increase in modiolus, practically if this was to be achieved with reduction in density and without loss of strength.

The disadvantage of this material when compared to cast iron is its relatively poor damping capacity[58]. As a result it is more difficult to minimize vibration and noise and there is the possibility of a reduced fatigue strength. However, research is still being directed toward improving the wear-resistence of the alloy to increase its potential as a replacement of cast iron.

2.10. Scope of the Present Work:

In view of the foregoing discussion, the main objects of the present study are :

1. To develop an aluminium-silicon piston alloy from locally available scrap materials.
2. To investigate the effects of modification, cooling rate and heat treatment on the morphology of Si,
3. To study the effect of heat treatment on stress relieving during casting, and finally
4. To motivate the local industries to adopt the technique for better performance of the piston, piston ring, liners, cylinder blocks etc.

CHAPTER-03

3. EXPERIMENTAL PROCEDURE

3.1. Introduction:

A number of castings were carried out to determine the effects of cooling rate, modification and heat treatment on the micro-structure and properties of the Al-Si piston alloy. In order to achieve these objectives, locally available scrap pistons were used as basic raw materials. First of all, scrap pistons were melted in the furnace to make ingot for piston alloy and then chemical analysis were carried out to determine its composition. Details of the experimental procedure are furnished in the following sub-sections.

3.2. Pattern Preparation:

A special type of wooden pattern was selected for making stan-dard tensile specimens in the as-cast conditions. The detail drawing of the pattern is shown in Figure 7. The pattern was made on the basis of available informations[58-60].
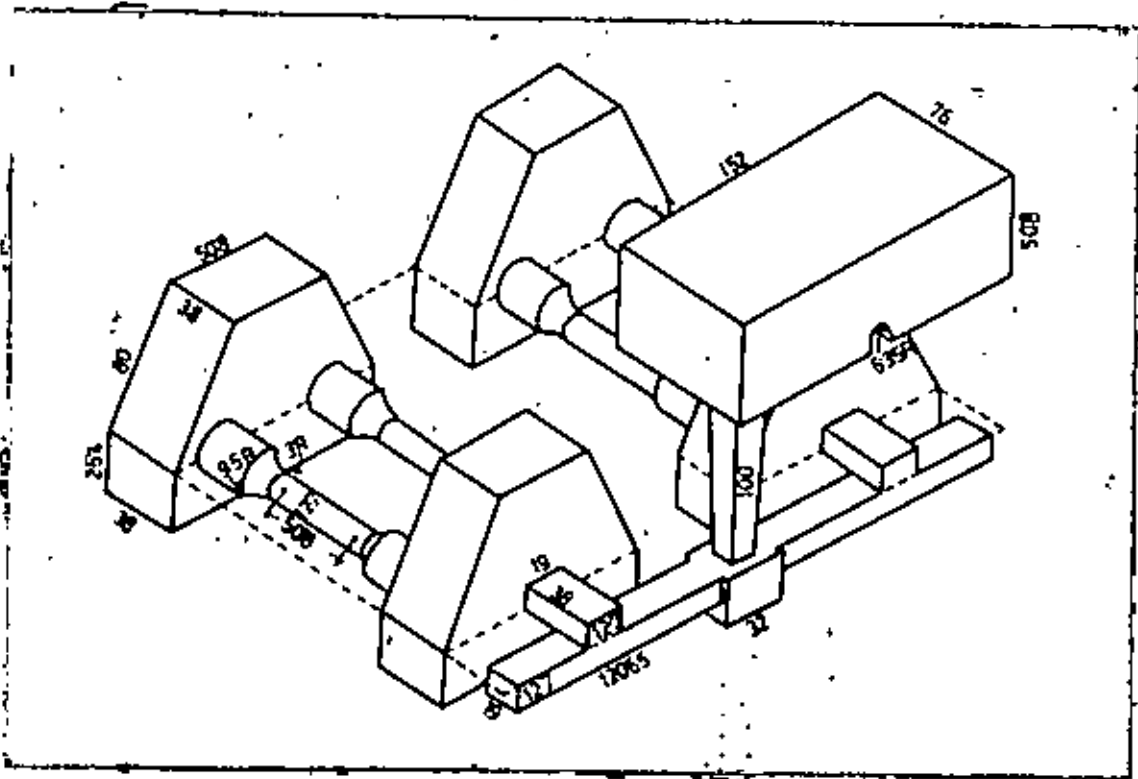
Fig. 7. The wooden pattern with four identical tensile specimens.
All dimensions are in mm.

3.3. Moulding Materials:

The moulding materials should be such that mould cavity retains its shape till the molten metal solidifies and castings are made in (i) Permanent moulds, which are made of metals and alloys, and (ii) Temporary moulds, which are made of refractory sands. In the present case, cast iron mould for chill casting and green sand mould for sand casting were used, details of which are given below:

3.3.1. Chill Casting:

For chill casting, cast iron keel block mould was used. Its shape and size is shown in Figure 8. Before casting, the keel block mould was properly dressed with alumina coating and heated with gas flame to remove any moisture and to decrease the temperature gradient between the mould and the molten alloy.

3.3.2. Sand Casting:

For sand casting, green sand mould was used. In the present work, the natural sand was considered as main moulding material.
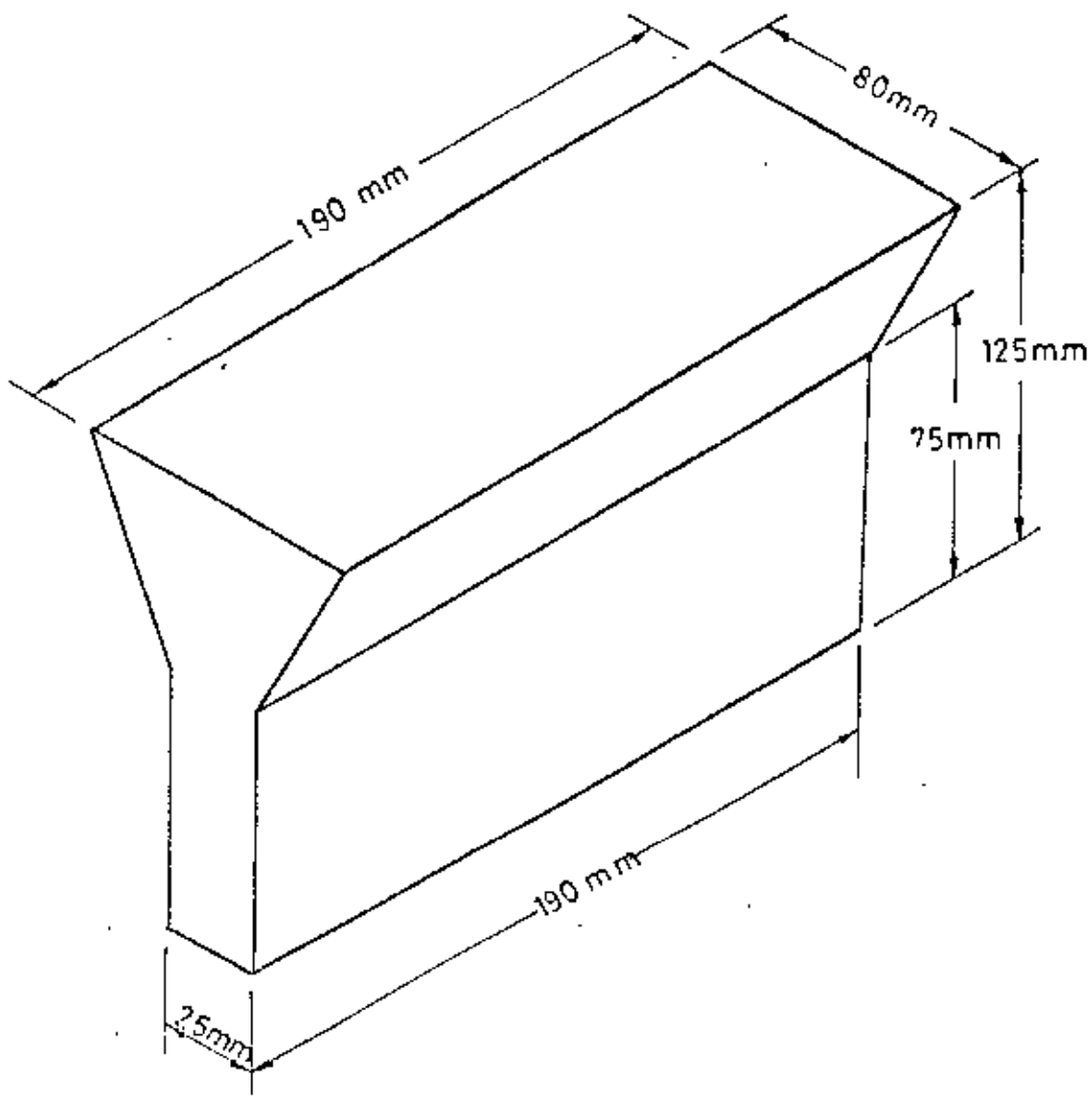
FIG. 8.. CAST IRON KEEL BLOCK MOULD.

The A.F.S. grain fineness number of the sand was measured by Tylor's Sieve Shaker and was found to be about 170. The moulding aggregate consisted of mainly sand and 18% clay to which 5-6% water was added. The mould used for the experiments contained four identical test pieces having a common sprue as shown in Figure 7.

3.4. Charge Materials:

Locally available scrap pistons (broken automobile pistons) were used as the main charge materials. Analysis of the material was shown in Table-1. The analysis of different elements were carried out using standard procedures[51].

TABLE -1

Chemical composition (wt%) of the Aluminium-Silicon Piston Alloy,

Si	Cu	Pb	Fe	Mn	Mg	Ni	Zn	Sn	Al
12.2	0.85	0.10	0.86	0.11	0.75	2.5	0.10	0.12	Rem.

Strontium (0.1%), in the form of an Al-14% Si-10% Sr master alloy was used as a modifying agent. The refine structure and properties reach a maximum at a strontium concentration of about 0.1%, then tend to decrease with further strontium additions beyond this level. It was added to the charge at the start of the melting. This temper alloy was cut into small pieces (3 to 10 mm) and put at the bottom of the crucible[29]. This allows sufficient time to dissolve the master alloy and to react effectively with the piston alloy.

3.5. Melting and Casting:

Melting of the charge materials and casting of the melt have been carried out simultaneously. The details are outlined below:

3.5.1. Melting:

The melting was carried out in a natural gas fired crucible furnace. The required amount of piston alloy was kept in a graphite crucible which was placed in the furnace and heated slowly. When the melt was ready, it was stirred with a mild steel rod. The stirrer was pre-coated with alumina wash to minimize contamination of the melt and carefully pre-heated.

After raising the temperature of the furnace well above the melting range of the aluminium-silicon alloy, the melt was kept at that temperature for sufficient time. The crucible was then removed from the furnace with the help of a clamp having a long pair of arms. In order to clean the melt, flux (NH_4Cl) was added into the crucible and stirring was continued for few seconds. Then the dross was skimed off from the top of the crucible with a alumina precoated steel spoon and the clean melt was poured into the moulds.

3.5.2. Temperature Measurement:

During melting, care was also taken to measure the superheating temperature as well as the pouring temperature of the melt. The temperature was measured with the help of a Digital Thermometer which gave a direct reading of $\pm 2^0$ accuracy.

The melt was superheated to about 750 C and was held at this temperature for about 5 minutes. For the best results, the pouring of the melt was done at 700-720 C[55].

3.5.3. Mould Preheating:

The sand mould was first dried naturally and then by gas flame prior to pouring the melt. The keel block was also pre-heated to

about 200 to 250 C before pouring the melt. Mould preheating is necessary to decrease the temperature gradient between the mould and the cooling substrate which tends to promote the grain refinement during solidification of the melt.

3.5.4. Casting:

After skimming off the top dross, the clean melt with a pouring temperature of 700-720 C was poured into the metallic mould and the sand mould. The molten alloy was poured into the mould in a continuous stream in order to avoid any turbulence, thus minimizing dross formation and hydrogen pick up in the casting. However, all of the operations were carried out so quickly that the temperature drop from 720 C was not more than 10 C. Each tensile specimen was individually marked for identification.

3.5. Heat Treatment:

Although a number of heat treatment process can be applied on the aluminium-silicon alloys but for present work, the full heat treatments (i.e., solution, ageing and precipitation treatments) were carried out according to the following procedure:

The specimens were solution treated at a temperature of 520 C (±5 C) in a resistance heating muffle furnace. The required time at this temperature was 8 hours for both chill and sand castings. They were then quenched in hot water bath at 60 C for 15 minutes. After removing the specimens from hot water, they were dried and kept in a freezer (-10 C) overnight. These specimens were again heated at 180 C (±5 C) for 8 hours, removed from the furnace and air cooled.

3.7. Specimen for Different Tests:

The tensile specimens were obtained from round, cast to shape and size, test bars from green sand moulds and the cast iron keel block chill mould. The chill cast specimens were cut from 'keel block' cast product. Standard tensile specimens with a nominal diameter and minimum parallel length of 13 mm and 57.2 mm respectively (shown in Fig. 9) were prepared from keel block. All chill cast specimens of standard 50.7±0.5 mm gauge length were used for tensile testing. But the as-cast (sand) specimens were tested without machining. Metallographic Specimens were also prepared from chill and sand cast products.
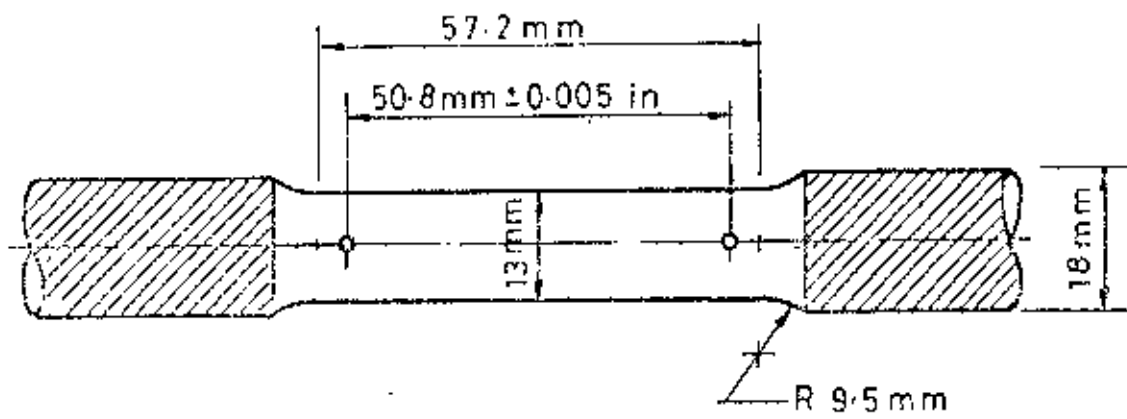
FIG. 9 . STANDARD ROUND SPECIMEN FOR TENSILE TEST.

3.7.1.Tensile Testing:

As-cast and heat treated under both modified and unmodified conditions were tested with a tensile testing machine to obtain UTS and percentage elongation. Tensile tests were conducted on a 50 ton of Tinius Olsen Testing machine using 5 ton scales. After breaking the specimens, surfaces were studied to assess the type of fracture occurred during straining. All the tests were carried out at room temperature.

3.7.2. Hardness Tests:

Brinell Hardness testing was conducted using Avery Brinell Hardness Testing Machine. In order to determine the Brinell Hardness of the test pieces, 10 mm diameter indentator and applied load of 500 Kg_f were used and the loading time was about 20 seconds. This procedure was maintained for all specimens.

3.7.3. Density Measurement:

In order to determine the density, the samples were polished and cleaned with soap water and dried at 110 C in the oven. Then each specimen was weighed in both air and water. The weight of each

specimen was measured by electronic balance (accuracy ±0.1 mg) and the observed density was thus calculated using the following well-known Archimedean method:

$$\text{Density } (\rho_0) = \frac{W_d}{W_a - W_h} \times \rho_w$$

where, W_a = weight of specimen in air

   W_w = weight of specimen in water

   ρ_w = density of water at room temperature.

3.7.4. Percentage Porosity Measurement:

For measuring the percentage porosity of the casting, it was necessary to determine the maximum density of the specimen. For this purpose, the specimen which was used for bulk density, was compressed 78-80% of its initial thickness so that the voids and pores are pressed together to make the sample pore-free[62,63]. Then the specimen was polished, washed, dried and weighed in the same manner as described in section 3.7.3. The percentage of porosity was then calculated using the following formula[62]:

$$\text{Percentage Porosity}(P) = \frac{\rho_{pfs} - \rho_0}{\rho_{pfs}} \times 100$$

where,

ρ_{pfs} = Density of the pore-free sample

ρ_0 = observed density of the sample

3.7.5. Stress Relieving Tests:

Stress relieving of cylindrical castings were accomplished by thermal treatment. This was done exactly in the same way as heat treatment operation was carried out. The peripheral length of the cylinder was measured first in the as-cast condition then thermal treatment was carried out for both the modified and unmodified samples. The cylinder was then sectioned by milling machine and the final peripheral length was measured again. The difference between the two readings (if any) was extension due to relieving of internal residual stress induced during solidification. If there is no extension, then the residual stress has been relieved due to thermal treatment. The procedure of measuring the residual stress for cylindrical casting by sectioning method has been adopted by several investigator[39,40].

3.8. Metallography:

The specimens were polished in the usual manner by emery paper. Final polishing was carried out with fine alumina powder (0.1 micron) by hand. This was necessary to remove any microscratches from the specimens.

After polishing, the specimens were cleaned by acetone and were etched in 3% HNO_3 and 2% aqueous hydrofloric acid (HF) solution. The etching time was about 30-40 seconds but repeated etching and polishing was necessary to reveal the structure. Microstructures of these specimens were examined under the optical microscope both in the etched and unetched conditions. Photomicrographs of the structures were taken as necessary to see the morphology of silicon in the presence and absence of strontium at fixed magnification (X100). Photomacrograph of the fracture surfaces of the specimens were also taken to assess the type of fracture in the casting.

CHAPTER-04

4. EXPERIMENTAL RESULTS:

4.1. Introduction:

The results of the present investigation have been presented in this chapter in tabular form and metallographic structures have been illustrated with suitable photomicrographs. For convenience, this chapter has been divided into two parts. The first part mainly deals with the effect of modification by strontium and the second part comprises the effect of heat treatment on structure and properties of modified and unmodified alloys. In each case, the effect of cooling rate has also been investigated.

4.2. Effect of Modification on Structure and Properties:

The results of the tensile test and hardness of aluminium-silicon piston alloy in the as-cast condition are shown in Tables 2 and 3, and graphically shown in Figs. 10 and 11. The photomicrographs of the structures of chill and sand cast samples are shown in Figs. 12 and 13.
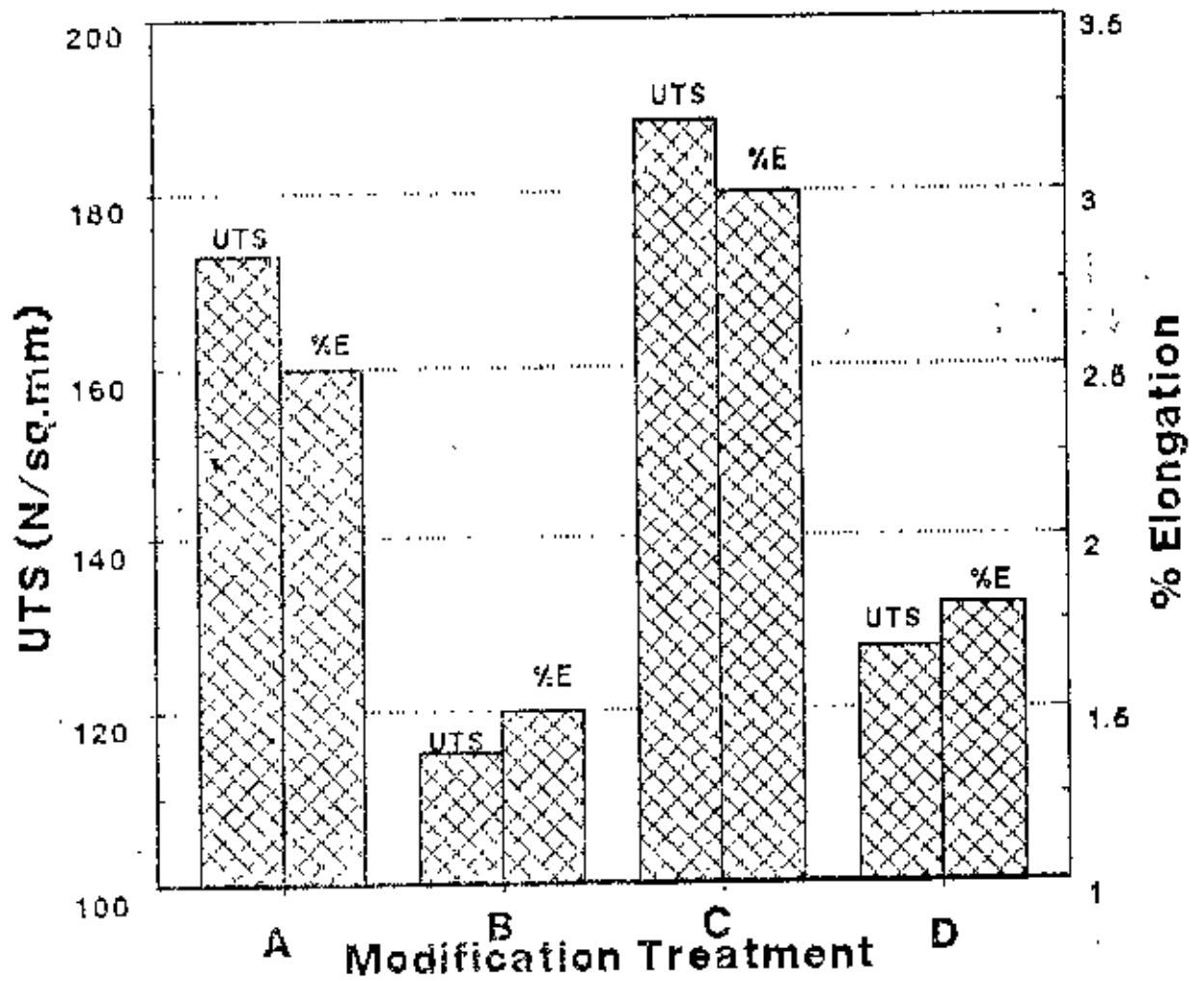
TABLE-2

Tensile Properties of Al-Si Piston alloy, as-cast condition,

Modification	Mould Type	UTS (N/mm^2)	Elongation,(%)
Unmodified	Chill	173	2.5
	Sand	116	1.5
Modified	Chill	188	3.0
	Sand	127	1.8

TABLE-3

Hardness (BHN) of Al-Si Piston alloy, as-cast condition:

Modification	Type of Casting	BHN
Unmodified	Chill	76
	Sand	65
Modified	Chill	88
	Sand	78

Fig. 10. Graphical representation of tensile properties of
Al-Si piston alloy, as-cast condition.

Fig. 11. Graphical representation of hardness of Al-Si Piston alloy, as-cast condition.

A & B= unmodified chill & sand cast respectively

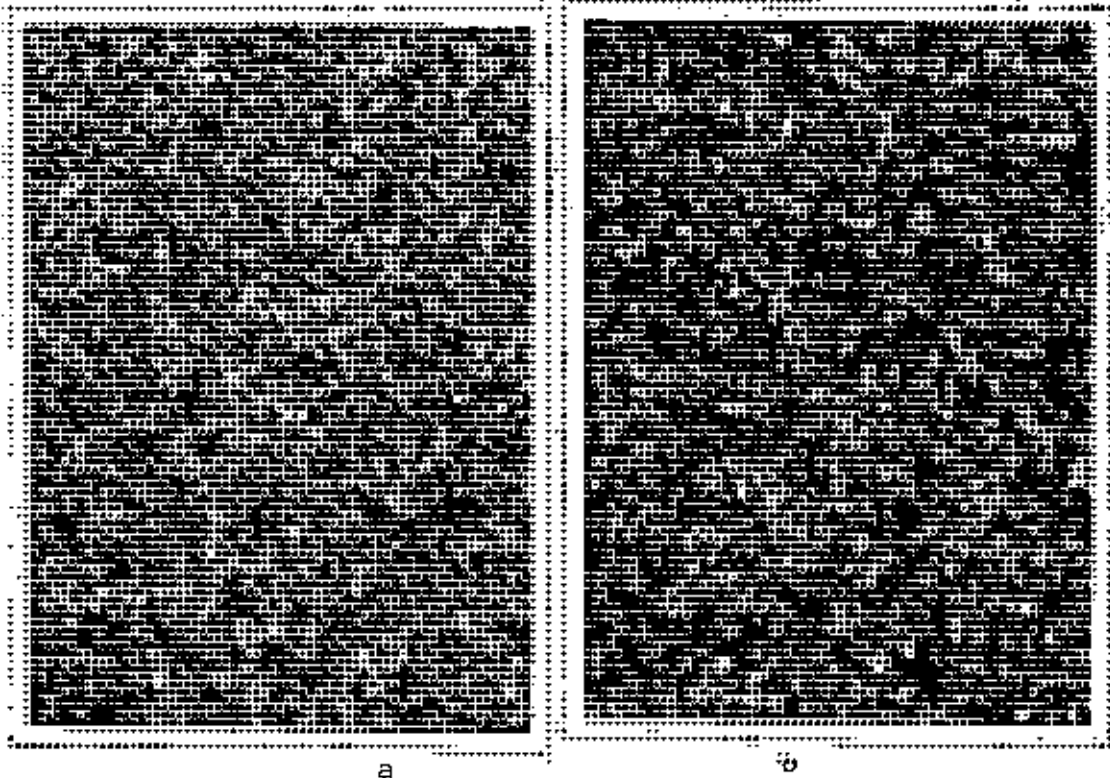C & D=modified chill & sand cast respectively

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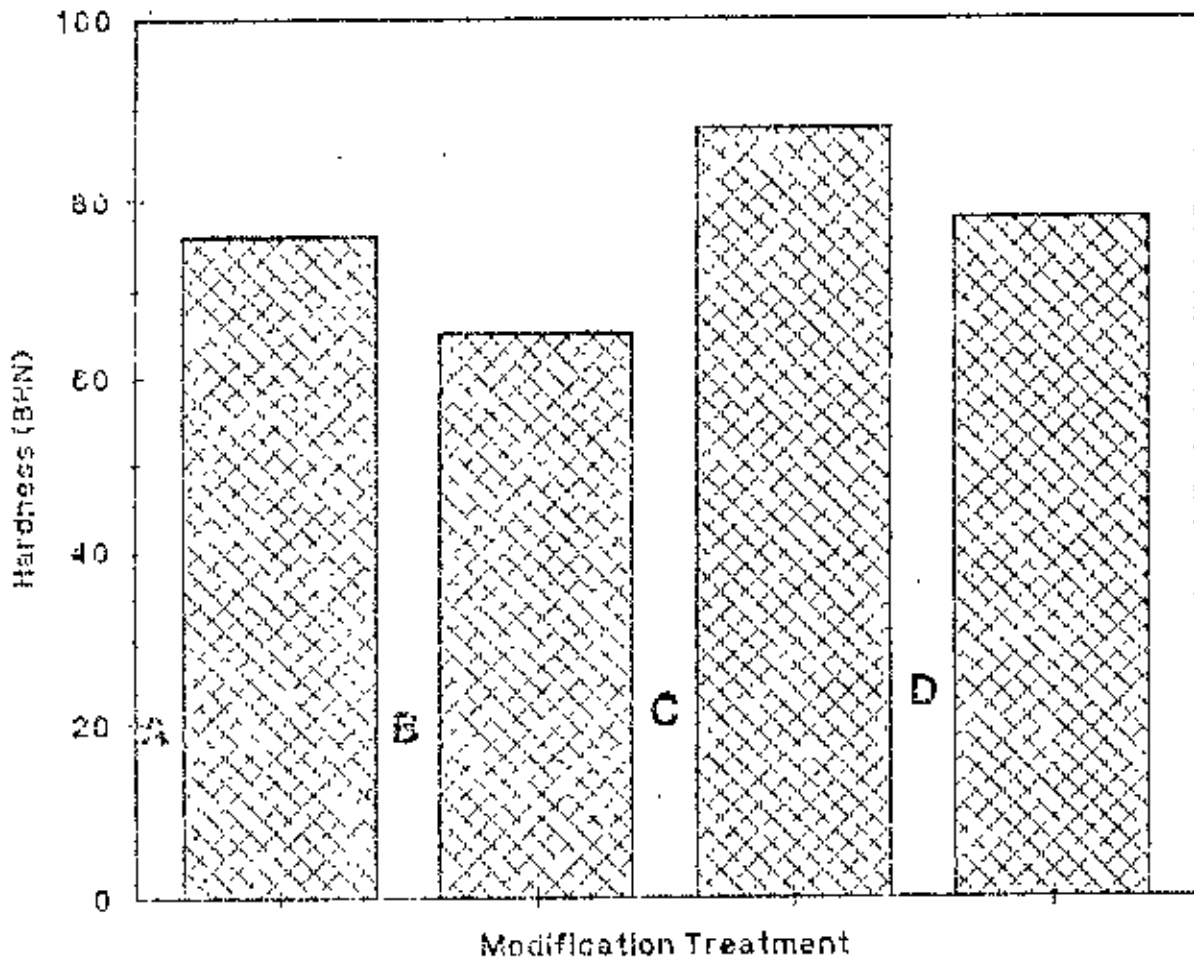
Fig.12.   Unmodified Al-Si Piston alloy (12.2% Si), chill cast,
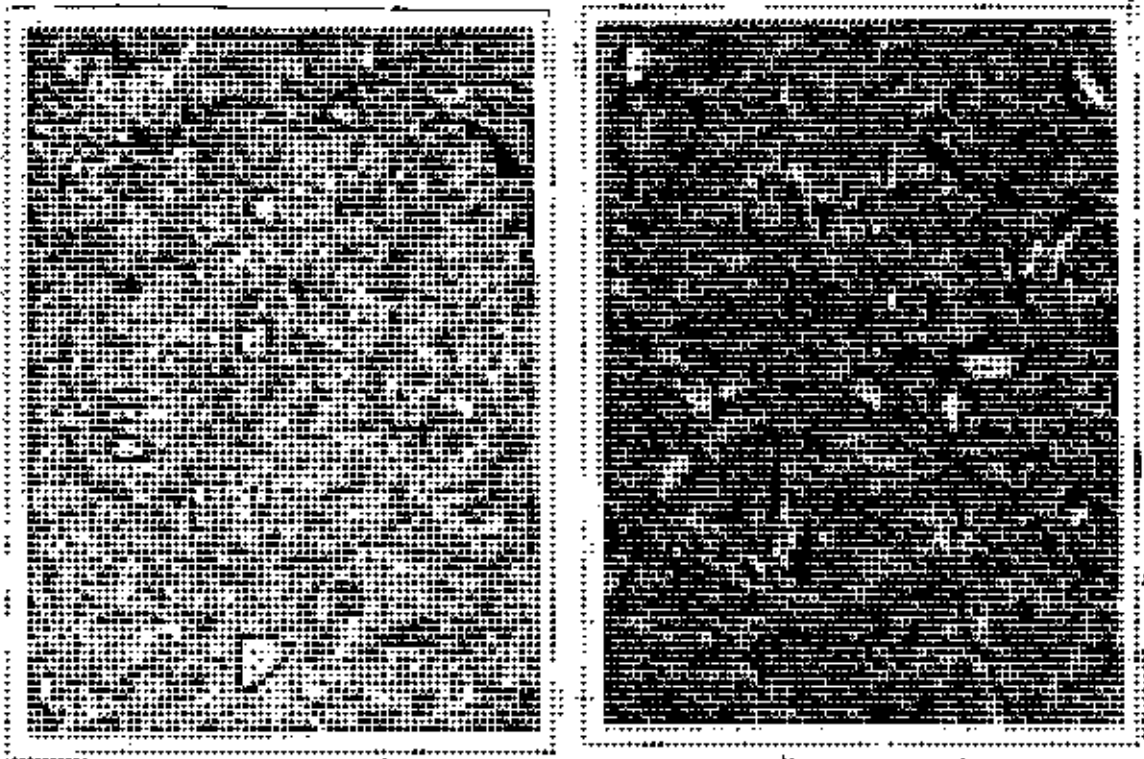   a unetched b etched, X100.

Fig.13.   Unmodified Al-Si Piston alloy (12.2% Si), sand cast,
         a unetched b etched, X100.

It can be seen that, for unmodified alloy, the Ultimate tensile strength, percentage of elongation and hardness of chill cast specimens are as 173 N/mm^2, 2.5% and 76 HB, respectively, whereas for the sand cast specimens, they are about 116 N/mm^2, 1.5% and 65 HB, respectively. It can also be seen that, for both rate, of cooling, these values are increased when the alloy is modified with strontium.

The percentage porosity of both chill and sand castings are shown in Table 4, and graphically presented in Fig. 16. It can be seen that the percentage of porosity for chill and sand cast unmodified specimens are about 0.77 and 1.07 respectively , whereas for modified alloys, they are about 1.11 and 1.44 respectively.

4.3. Effect of Heat Treatment on Structure and Properties:

The detailed results of heat treated modified and unmodified samples are shown in Tables 5-7 and have been graphically shown (in the bar form) in Figs. 17 and 18. Photomicrographs of the modified and unmodified specimens for both rates of cooling are shown in Figs. 19 to 22.

It can be seen that the ultimate tensile strength, percentage elongation and hardness of heat treated unmodified chill cast specimens are as 278 N/mm^2, 1.5 % and 122 HB, respectively, whereas for sand cast specimens they are as 230 N/mm^2, 1.0 % and 109 HB, respectively. These values are also increased when the alloy is modification and heat treated.
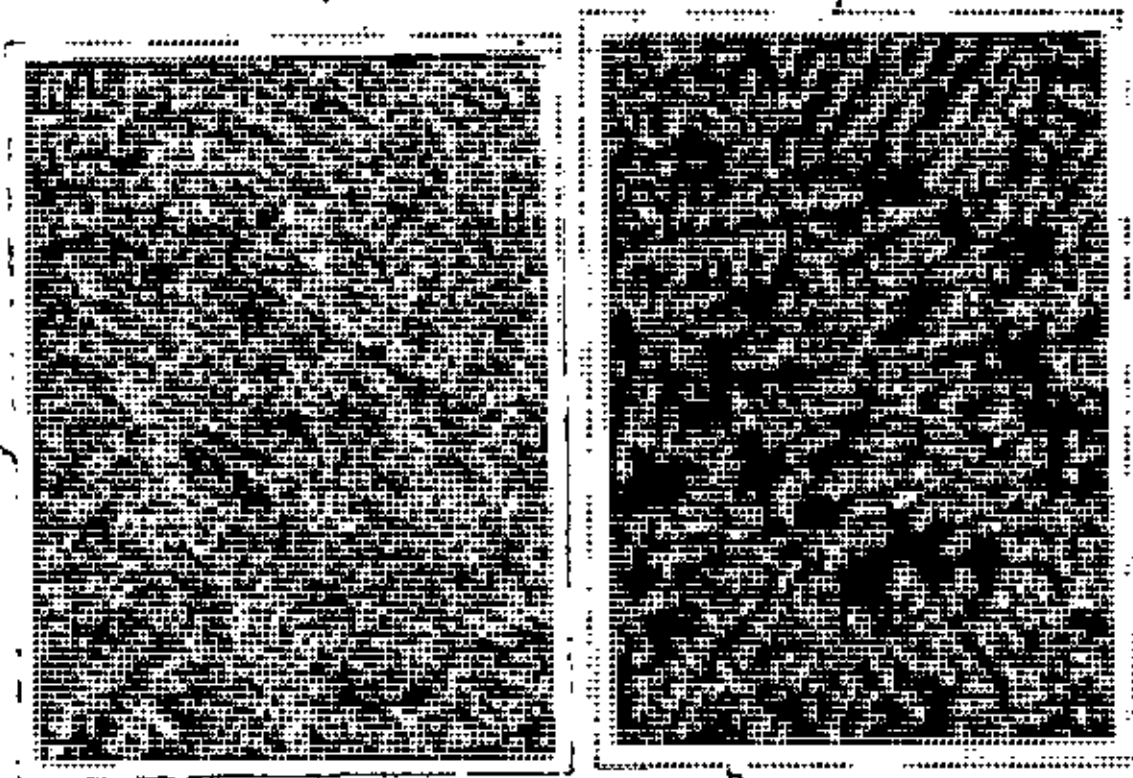
Fig.14. Modified Al-Si Piston alloy (12.2% Si.).1% Sr), chill cast, a unetched b etched X100.
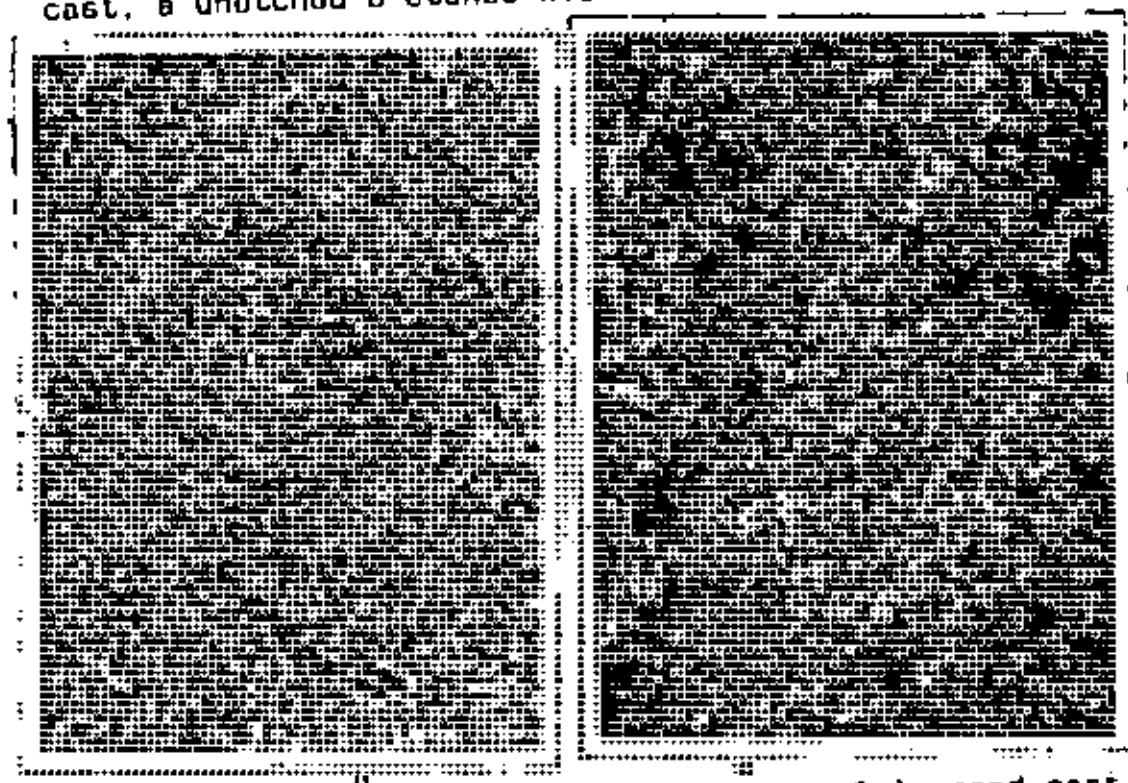
Fig.15. Modified Al-Si Piston alloy (12.2%, 0.1% Sr), sand cast, a unetched b etched X100.

TABLE-4

Porosity of Al-Si Piston alloy:

Modification	Mould Type	Density, g/cc	Max.Density (g/cc)	Porosity (%)
Unmodified	Chill	2.689	2.71	0.77
	Sand	2.67	2.699	1.07
Modified	Chill	2.67	2.7	1.11
	Sand	2.66	2.699	1.44
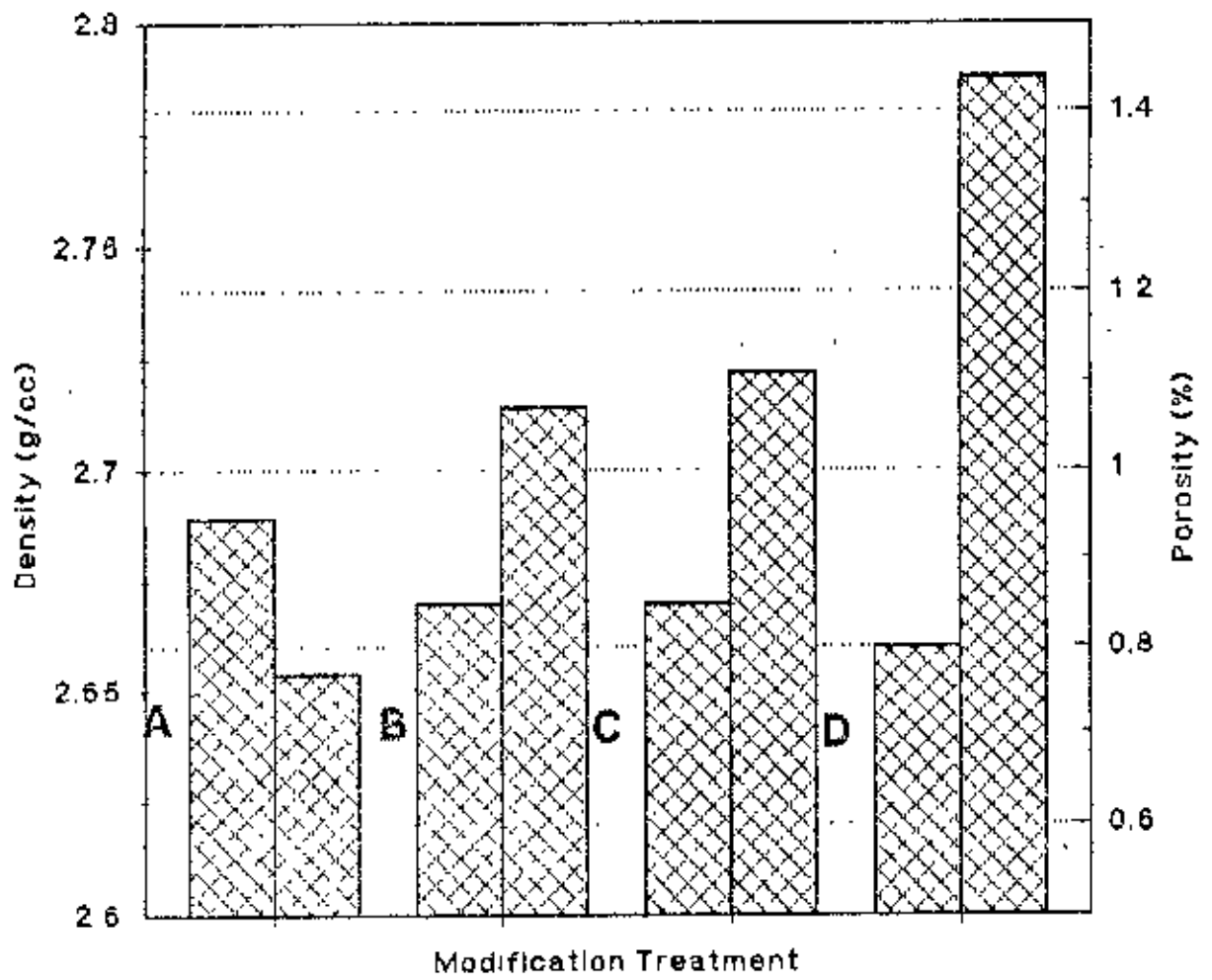
A & B=unmodified chill & sand cast respectively
C & D=modified chill & sand cast respectively

Fig.16. Graphical representation of density and porosity

of Al-Si Piston alloy

TABLE-5

Tensile Properties of Al-Si Piston alloy, heat treated condition:

Modification	Mould Type	UTS, (N/mm^2)	Elongation,(%)
Unmodified	Chill	278	1.5
	Sand	230	1.0
Modified	Chill	295	2.0
	Sand	244	1.5

TABLE-6

Hardness (BHN) of Al-Si Piston alloy, heat treated condition:

Modification	Type of Casting	BHN
Unmodified	Chill	122
	Sand	109
Modified	Chill	129
	Sand	118

TABLE-7

Peripherial Expansion of Cylindrical Casting (Al-Si Piston alloy) due to Heat Treatment

Modifica-tion	Peripherial Length (mm)		Difference (mm)	Extension (%)
	Before HT	After HT		
Unmodified	233.2	236.6	3.3	1.42
Modified	234.5	237.5	3.0	1.27
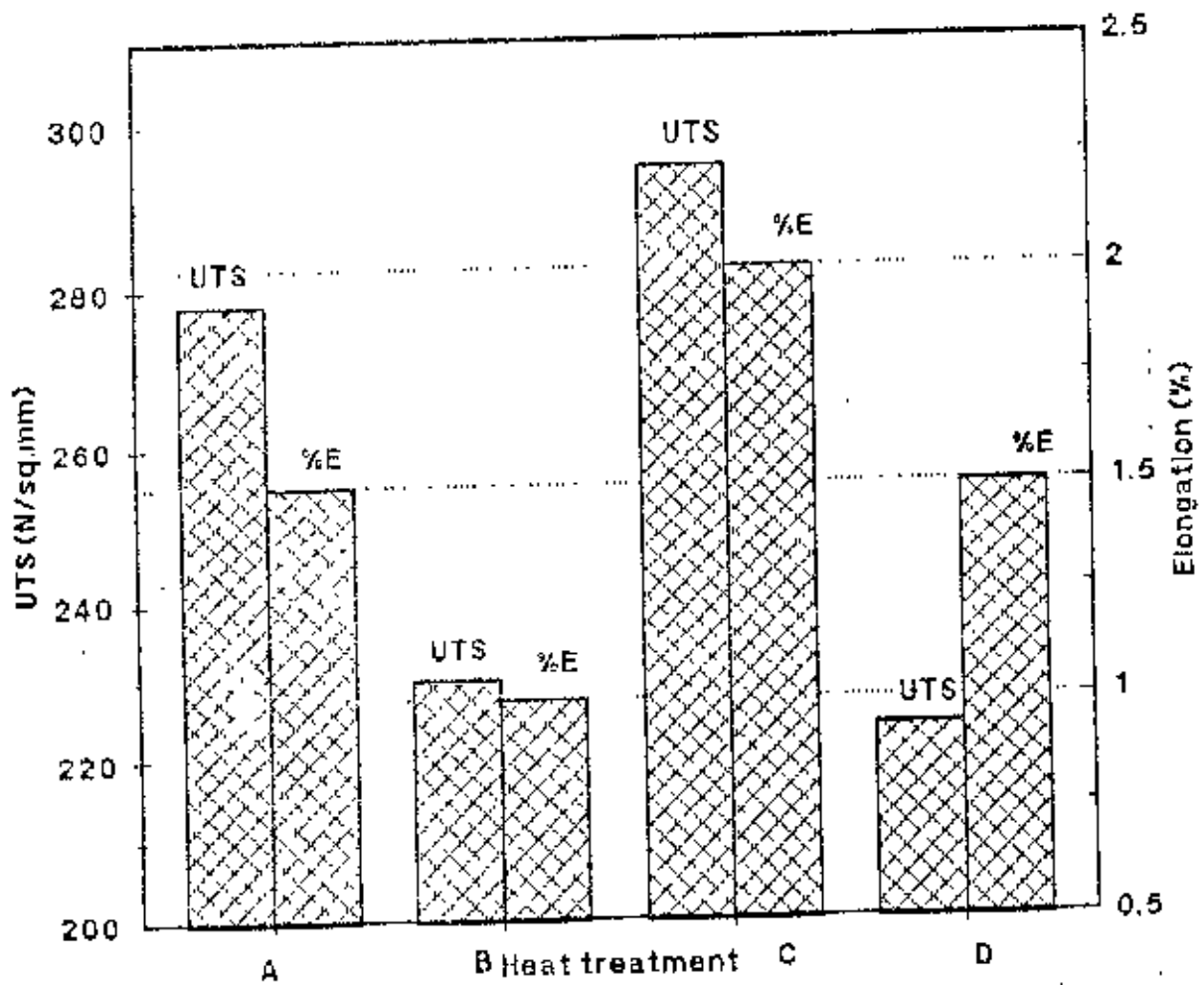
A & B=unmodified HT chill & sand cast respectively
C & D=modified HT chill & sand cast respectively

Fig. 17. Graphical representation of tensile properties
of Al-Si Piston alloy, heat treated condition.
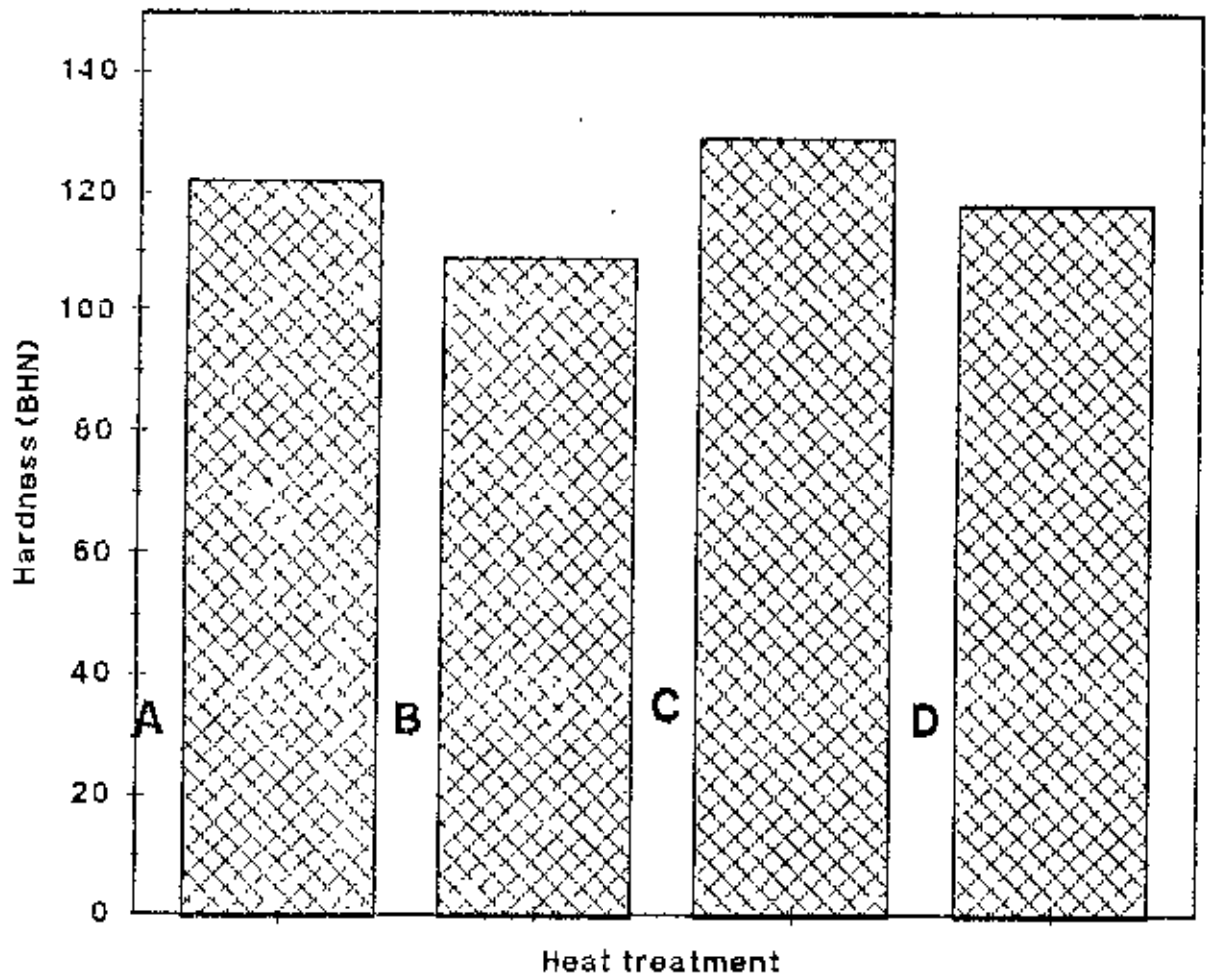
A & B=unmodified HT chill & sand cast respeotively
C & D=modified HT chill & sand cast respectively

Fig. 18. Graphical representation of hardness of Al-Si
Piston alloy, heat treated condition.
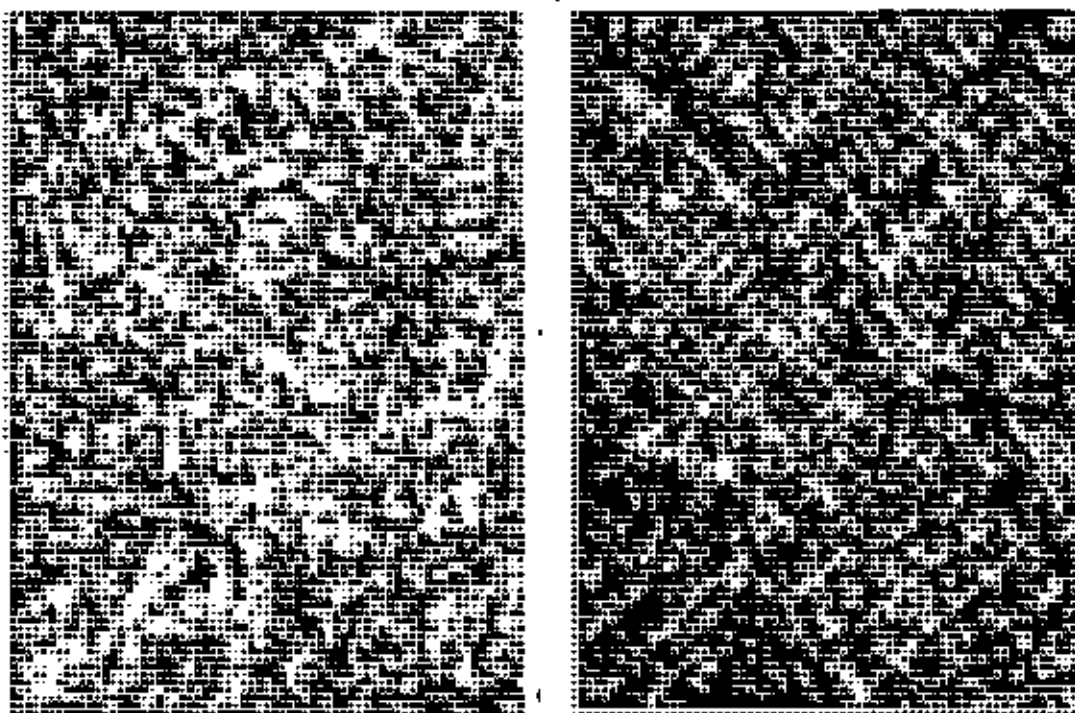
Fig.19. Unmodified heat treated Al-Si Piston alloy (12.2% Si).
chill cast, a unetched b etched, X100.
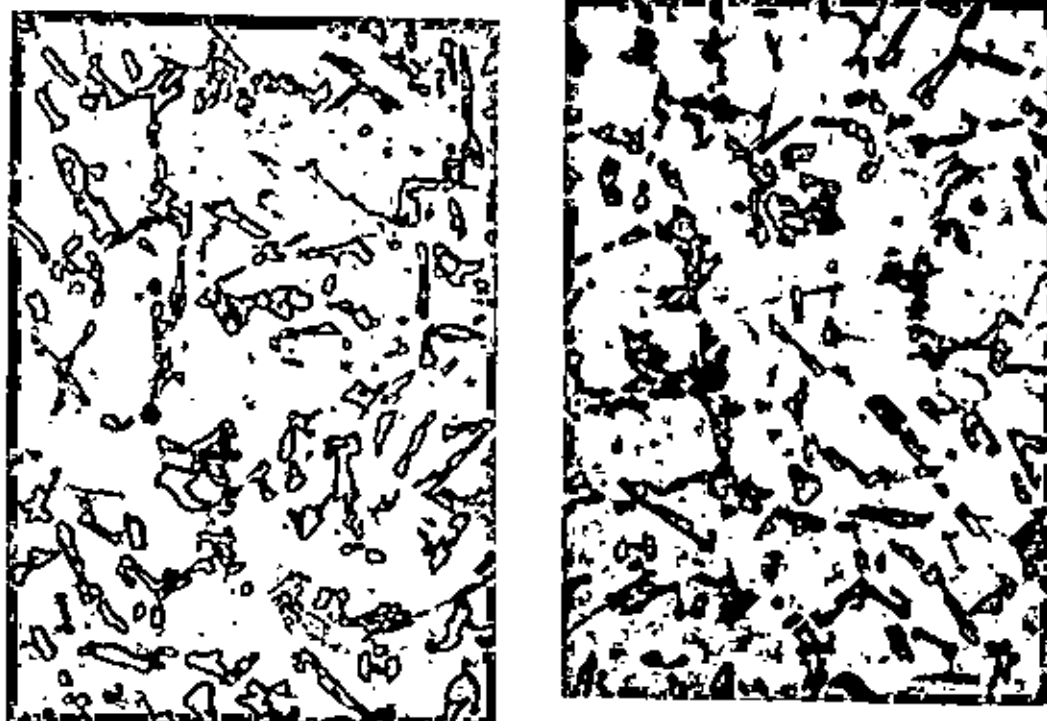
Fig.20. Unmodified heat treated Al-Si Piston alloy (12.2% Si),
sand cast, a unetched b etched, X100.
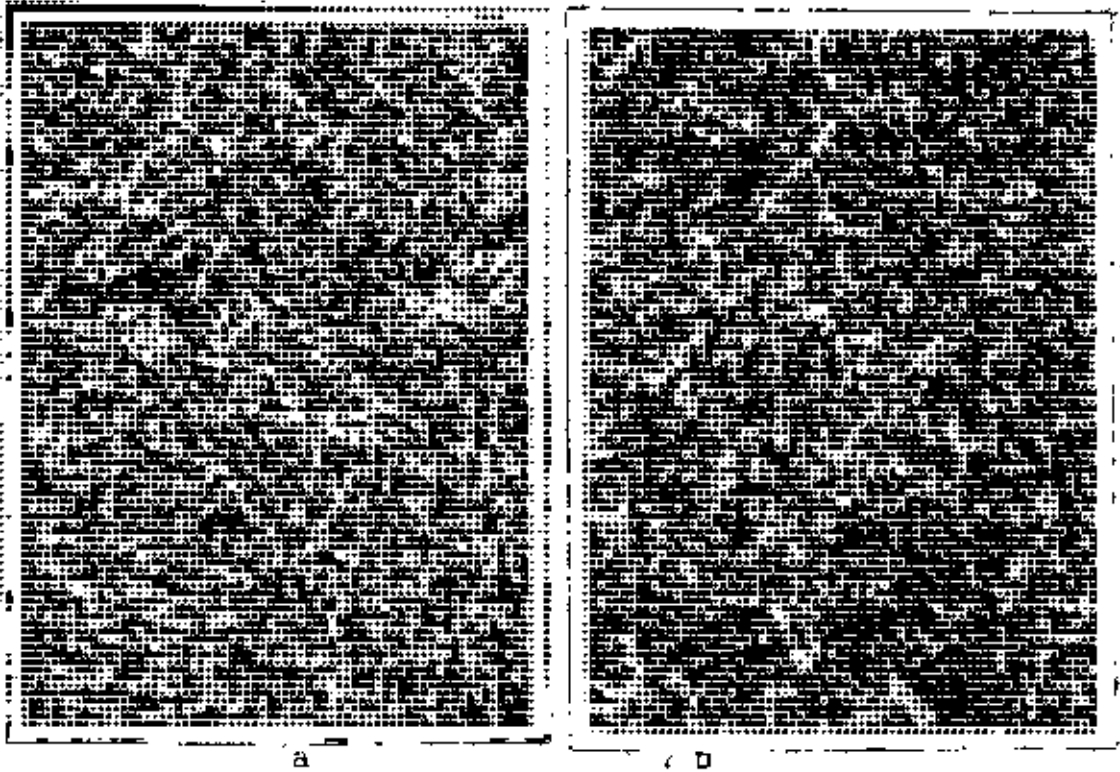
Fig.21. Modified heat treated Al-Si Piston alloy (12.2% Si), chill cast, a unetched b etched, X100.
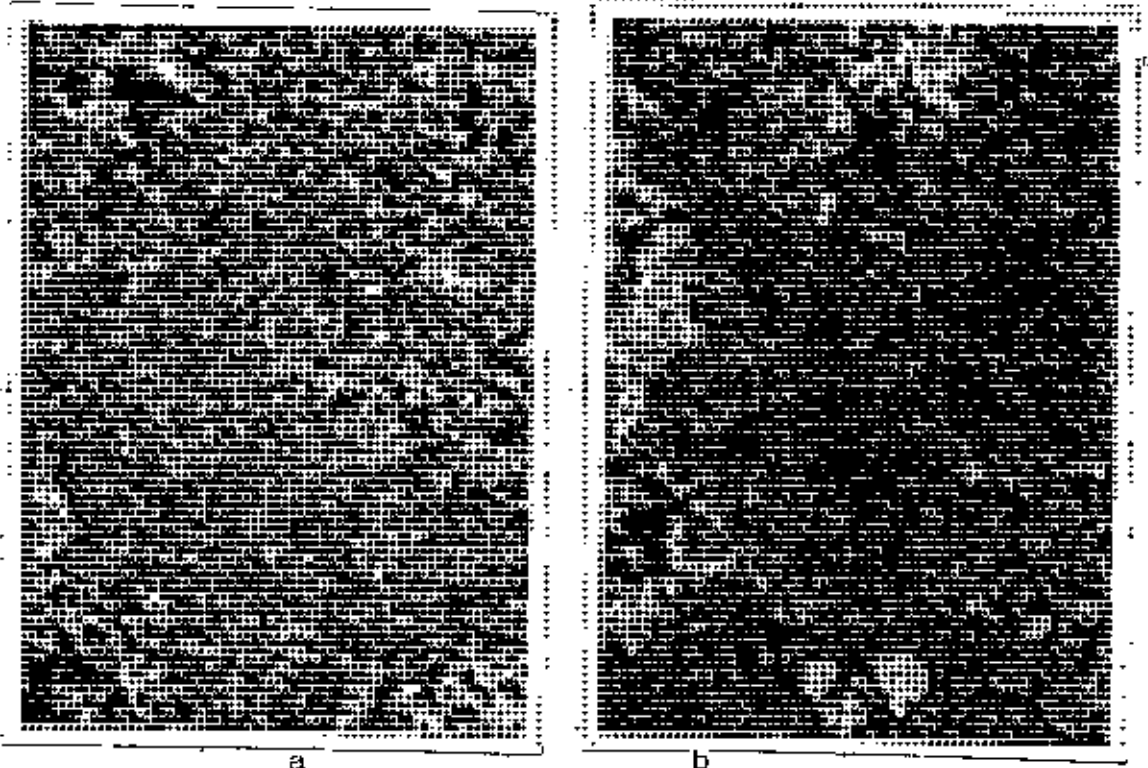
Fig.22. Modified heat treated Al-Si Piston alloy (12.2% Si), sand cast, a unetched b etched, X100.

4.4. Effect of Modification and Heat Treatment upon Stress Relieving

The results of as-cast unmodified and modified specimens are shown in Table-8, whereas Table-9 shows the results of heat treated castings. It can be seen that the extension due to relieving of internal residual stress of unmodified and modified specimens are as 2.5 mm and 1.0 mm respectively, whereas the values in the heat treated condition are as 1.0 and nil.

TABLE-8

Stress relieving (expressed as an extension) of Al-Si

Piston alloy, as-cast condition:

Modification	Peripheral length, (mm)		Extension (mm)
	Before sectioning	After sectioning	
Unmodified	232.5	235.0	2.5
Modified	236.0	237.0	1.0

TABLE-9

Stress Relieving (expressed as an extension) of Al-Si Piston alloy,

heat treated condition:

Modification	Peripheral length, (mm)		Extension (mm)
	Before sectioning	After sectioning	
Unmodified	236.5	237.5	1.0
Modified	237.5	237.5	nil

CHAPTER-05

5.DISCUSSION ON THE EXPERIMENTAL RESULTS

5.1. Introduction:

The experimental results so far obtained during present investigation show that the change of process variables have a great effect on structure and properties of aluminium-silicon piston alloy. These have been discussed in details in the following sub-sections:

5.2. Effect of Cooling Rate:

Differences in cooling rate markedly affect the structure and properties of the modified and unmodified castings.

5.2.1. Structure:

Figs. 12 and 13 show the microstructures of chill and sand cast specimens respectively in the unmodified condition. The figures show that the amount of the primary silicon is less in chill cast specimen than that of sand cast. Microstructure of the sand cast specimen consists of α-aluminium dendrites, acicular silicon and primary silicon plates and the structure is less refined than the chill cast. Cooling rate controls the primary dendrites. During metallographic examination, it is evident that highly branched and feathery dendrites resulted from rapid cooling rate due to the restriction of the recalescence, whereas low rates led to the

formation and development of primary silicon plate. Fine grain structure promotes improved mechanical properties, while coarse grain structure, by emphasizing grain boundary effects, results in lower mechanical properties (Table 2 and 3 and Figs. 10 and 11). The reason for fine structure in the chill cast specimen may be discussed as follows: The separation of the liquid into two solid phases can take place only by diffusion just before solidification. The distance through which this diffusion can occur depends on the time available, which in turn depends on the rate of solidification. Thus, rapid cooling will allow a short time for diffusion at the liquid-solid interface, and a fine structure will result[64,65]. Thus higher the cooling rate finer the structure and vise versa.

5.2.2. Properties:

It can be seen from Tables 2 and 3 and Figs. 12 and 13 that faster cooling rate improve the tensile properties and hardness of the aluminium-silicon piston alloy. Since the degree of undercooling is less in slower rate of cooling (i.e., sand cast specimen) and fewer nuclei are available for growth which eventually lead to the formation of comparatively coarse crystalline structures and hence inferior tensile properties. The hardness of fastly cooled (i.e. chill) casting is also higher than those obtained from comparatively slowly cooled casting (Table 3).

It can be seen from the measurement of porosity of the specimens (Table-4 and Fig. 16), that the percentage porosity is higher in sand cast specimen than chill cast specimen. The large pores (greater porosity) in sand cast is formed due to the coagulation of

many micro-pores and high degree of hydrogen and water absorption
by the melt from the green sand mould and their rejection upon
solidification. Furthermore, in the sand cast bars, the pores occur
over a wide area, and are either interconnected fissures, or of
unconnected interdendritic oval shape.Due to higher porosity in
sand cast specimen both physical and mechanical properties are
inferior to those of chill cast specimen.

Berger[34] has studied porosity in aluminium and magnesium alloys and
has shown that, faster cooling rate show higher density than that
of slower rate of cooling. Thus the porosity depends upon the
solidification rate as well as the freezing range of the alloy.

5.3. Effect of Modification:

Strontium treatment has proved to improve the various
characteristics of the aluminium-silicon piston alloy, which are
discussed below.

5.3.1. Structure:

The extent to which strontium is able to refine the eutectic phase
of the structure mainly depends on its concentration in the molten
alloy before the commencement of solidification and also on the
growth rate induced. During melting, care was taken not to allow
the melt temperature to exceed 750 C, since the action of strontium
becomes progressively less effective above that temperature. This
melting procedure was adopted in the present investigation to

modify the alloy effectively. Since modifying elements depress the nucleation temperature, they also lower the growth temperature and change the growth morphology from coarse plate to apparently globular shape. Thus better properties of the alloy were obtained due to structural modification.

The microstructure of modified specimens show (Figs. 14 and 15) that the aluminium matrix contains large amount of rounded silicon with no primary silicon. The silicon crystals are predominantly of the feathery or star shaped type (Fig.14). Actually the nucleation and growth process affects appreciably the structure of the aluminium-silicon alloys both directly and indirectly[66]. When relatively small suppercooling is induced by the modifier, the stability of the joint growth of planes is disrupted. At the same time, the colony-like structure of the modified aluminium-silicon eutectic indicates a connection between the planes in the process of solidification. In this case the leading phase is the aluminium component, which during joint growth will outstrip the growth of silicon crystals, tending to surround them[67,68]. At the same time, the presence of strontium, the surface tension between aluminium and silicon are reduced. The result is that aluminium solidifies around particles of silicon, blocking them from the liquid. Due to the periodic supersaturation of the liquid with silicon, the silicon phase wedges out at the solidification front and are immediately surrounded by aluminium phase.

Modification by strontium changes the mode of solidification of the eutectic so the modified eutectic crystallizes with aluminium crystals in the lead instead of silicon crystals, as in the unmodified alloy. The change of lead in eutectic crystallization changes the structure of eutectic from a mixture of two continuous interpenitrating phases one of which is brittle, to that of a

discontinuous brittle phase imbedded in a soft matrix. This changes
of structure produces the improvement of mechanical properties,
which is the characteristic of modification.

The modified eutectic alloy also shows rod-like, (Fig. 15) growth
of silicon rather than plate-like, (Fig.13) as obtained in
unmodified alloy. When the aluminium-silicon eutectic piston alloy
is cast without modification, large primary silicon crystals are
seen in the structure (Fig.13). This characteristic has an
unfavorable effect on castibility and also on the technological
properties of the alloy.

5.3.2. Properties:

Tables 2 and 3 show the tensile properties and hardness
respectively, of the modified alloy. It can be seen that both
chill and sand cast modified specimens show higher UTS, %
elongation and hardness than the unmodified ones. Similar
observations were also reported by others[26,69,70].

In the present investigation, addition of strontium exhibits
substantial increase in tensile properties of the alloy. This
increase might be due to modification of the structure which
changes the shape of the eutectic silicon "coral" in the aluminium-
matrix, i.e., from a needle-like to a rounded morphology (Figs.14
& 15). The higher strength and ductility of chill cast specimens
result from the combined effect of rapid cooling and modification.

It is also noticeable from the Table 4 and Fig.16 that the density of the modified alloy is somewhat lower than the unmodified ones. The reason for slight lower value may be due to oxidation reaction of the strontium alloy[71]. As regards the microstructure of the modified alloy (Fig.15) it contains some holes and voids specially in the sand cast specimens which causes lower density that is some what higher porosity of the alloy.

However, a close examination of all modification results obtained in this investigation (Table 2, 3 and Figs. 14, 15) shows that an increase in mechanical properties is usually accompanied by the grain refinement.

5.3.3. Fracture Surface:

The appearance of the fracture surfaces after tensile testing also show the differences (Figs. 23 and 24). The fracture surface of the unmodified alloy have a lustrous, well-faceted brittle appearance which resembles the appearance of brittle silicon phase, whereas the modified surfaces have a lighter, silky fracture which suggests that fracture has occurred largely through the ductile aluminium-matrix. In the first case, the fracture follows the continuous brittle phase, whereas in the second case the brittle phase is discontinuous and the fracture goes through the plastic aluminium phase. Due to continuous breaking-up of the brittle silicon skeletons by modification, this is most probably the another cause of increasing the strength and ductility of the modified alloy.
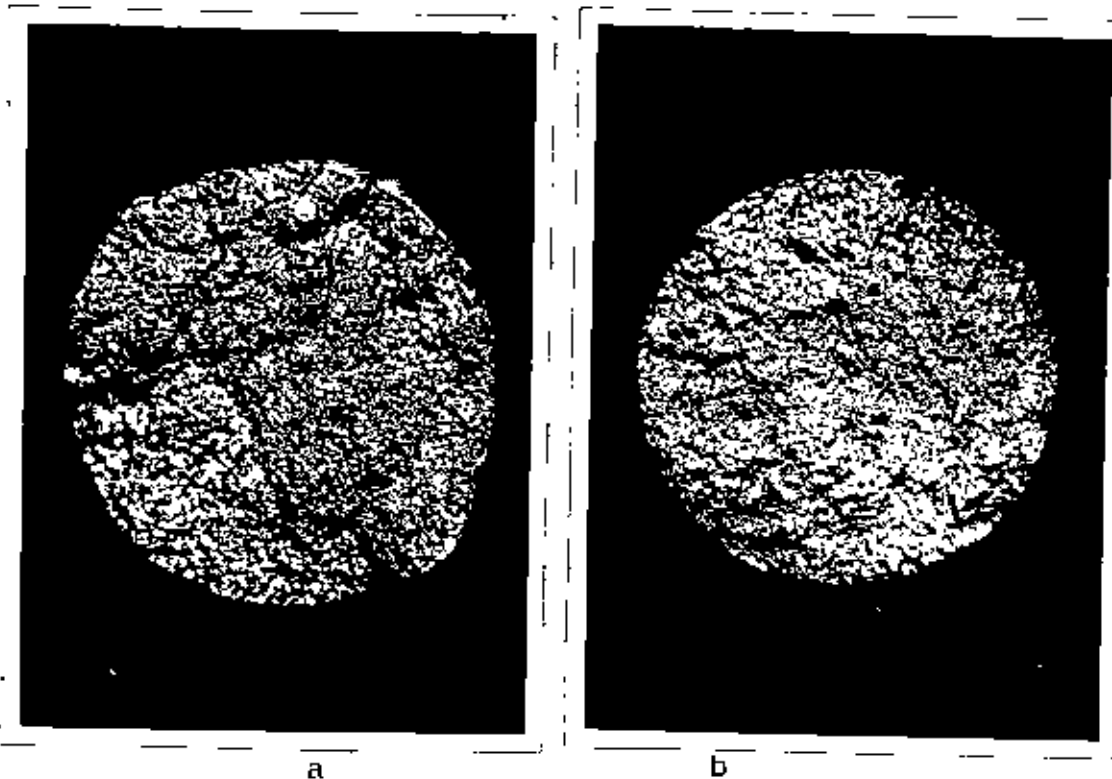
Fig.23.   Fracture surface of Al-Si Piston alloy, a unmodified
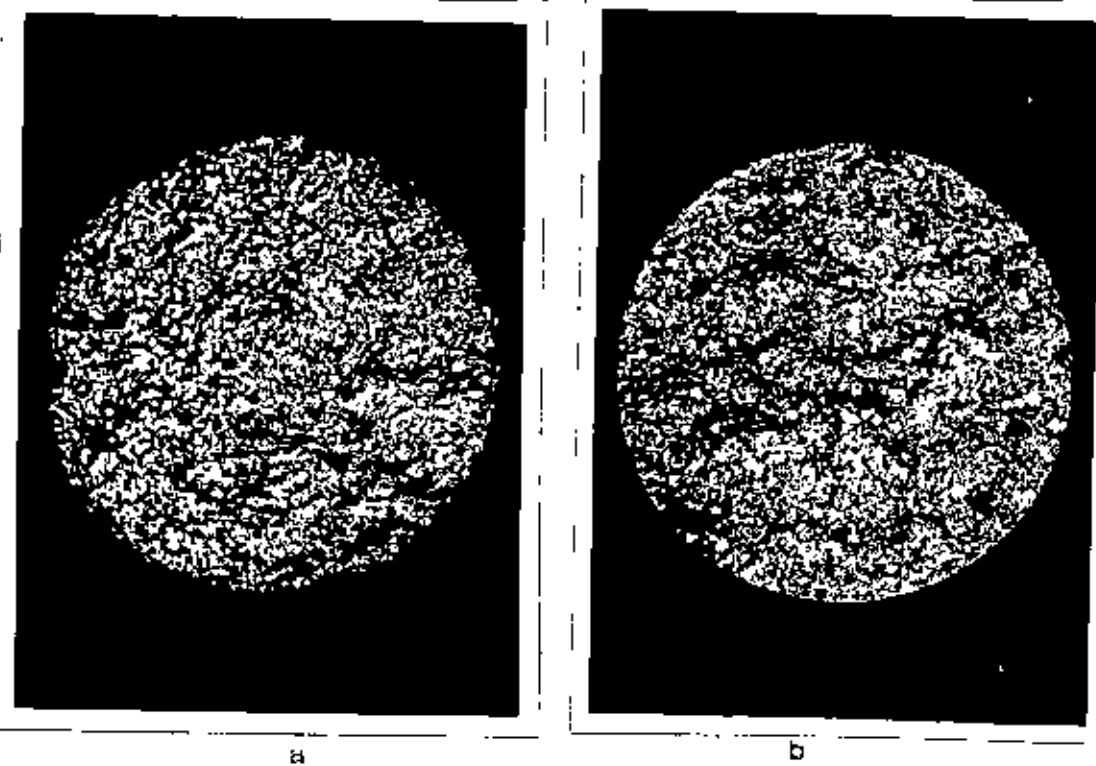   chill b unmodified sand; X5.

Fig.24.   Fracture surface of Al-Si Piston alloy, a modified chill
           b modified sand; X5.

5.4. Effect of Heat Treatment:

The effect of full heat treatment for both modified and unmodified alloys have led to essential changes in structure and properties of aluminium-silicon piston alloy. These can be discussed in the following sub-sections.

5.4.1. Structure:

Some sort of structural refinement was achieved in both chill and sand cast specimens when full heat treatment operation was carried out in the present investigation. The microstructure obtained after full heat treatment are shown in Figs. 19 to 22. It can be seen that due to heat treatment both the primary silicon crystals and eutectic silicon needles show some spheriodizing i.e.the sharp corners become rounded and the equiaxed twin crystals (Fig 19) are found. In the modified heat treated alloys, the overall structures are refined eliminating primary silicon crystals.

The structure of aluminium-silicon eutectic alloy (Fig. 22) show the particles of Fe_3SiAl_{12} (gray, scriptlike) and Mg_2Si (black) in the aluminium-rich solid solution matrix. The present investigated alloy contains copper and nickel which enhanced the strength and hardness at elevated temperature. Such type of results were also observed by other researchers[45,46]. Hanafee[46], studied structure and properties of the LH-13 type alloy. His study showed that the presence of nickel within the range of 0.1-2.5% increased the hardness of the alloy. This was attributed to the dispersed compound in microstructure.

The effect of heat treatment is more significant in the sand cast
alloy compared to chill cast alloy. The reason might be that due to
chilling, the sharp corner of the eutectic silicon becomes rounded
and due to heat treatment, its effect is thus not pronounced fully.
On the other hand, in sand cast specimen, the eutectic silicon is
sharp and due to heat treatment, its sharpness somewhat reduced and
becomes sub-angular showing greater effect. Moreover, magnesium
silicide compound is finer and more evenly distributed in the chill
cast alloy, and further refining and dispersion resulting from heat
treatment occurs to a limited degree. Thus the tensile properties
are marginally affected for chill cast alloy, whereas the effect of
heat treatment on sand cast alloy is very pronounced.

When heat treated, the dendrite arm spacing is reduced[50]. Due to
completion of homogenization, more solutes come to the solid
solution. Hence, finer structure obtained, resulting greater
strength and hardness from the subsequent precipitation reaction.

5.4.2. Properties:

The changes of tensile properties and hardness due to heat
treatment of aluminium-silicon piston alloy have been shown in
Tables 5 and 6 respectively. A number of important points emerge
from the results obtained during this set of experiments. The
specimen having the highest UTS was found in the heat treated
condition, although in general the highest ductility (% elongation)
was found in the modified as-cast condition. When heat treated, it
forms a homogeneous single phase, followed by quenching to retain
the solute component in unstable state. Subsequent ageing and

precipitation treatment in the range of 180 C, the solute atoms were rejected and form a cluster as a coherent or semi-coherent precipitate. The strained field around a coherent or semi-coherent precipitate inhibit the movement of dislocations with increase in strength and hardness but decrease in ductility. This can be explained that the increase in strength due to heat treatment is balanced out by the decrease in ductility[57]. E.H. Dix[54] also observes that most of the heat treatable aluminium-alloys produce higher strength and lower elongation when ageing is done after quenching. When ageing is performed during present investigation after solution treatment and quenching, size of the casting (linearly) increased (Table-7). This may be due to the precipitation of alloying elements and also considerable growth occurred for silicon precipitation[60].

The peak values of the mechanical properties were reached at higher cooling rate of the heat treated modified alloy. The modification and heat treatment is superb for required properties rather than unmodified and unheat treated ones. This changes in mechanical properties, were mainly due to the size, shape and distribution of the magnesium silicide (Mg_2Si) precipitate particles during ageing. The piston alloy under investigation contains 0.75% Mg (shown in Table 1). It has been reported [10] that magnesium is one of the most important elements among the different alloying and impurity elements present in the aluminium-silicon alloys which confer strength, but its strengthening effect is fully observed only after heat treatment. Magnesium functions mainly as a precipitation hardener. Silicon of the alloy combines chemically with magnesium to form magnesium silicide (Mg_2Si) along the [100] direction of the aluminium matrix[72]. The compound, when finely dispersed by controlled precipitation during heat treatment, is responsible for strengthening the alloys.

Due to precipitation hardening or super saturated solid solution of the matrix, the alloy response to a lower ductility but higher hardness. However, substantially greater ductility is obtainable from the alloy submitted to special casting techniques (e.g.continuous casting) or to working (forged material); in these case, elongation of 5-10% may be attained[10]. The properties reach a maximum under heat treated conditions where the silicon-flakes of the eutectic phase of the castings are more uniform.

5.4.3. Residual Stresses:

The stress relieving data (measured as an extension) can be seen in Tables 8 and 9. After thermal treatment, the value of extension is found about 1 mm in case of unmodified specimen, whereas this value is zero in the modified one. The latter observation indicates that the residual stresses obtained from the test satisfy the condition of static equilibrium. When thermal treatment operation is carried out to a specimen, the objectionable residual stresses are removed. The internal residual stresses that is induced due to uneven cooling rate of castings or from other fabrication operations must be removed after thermal treatment undoubtedly.

Nowadays, the usual method of reducing internal stress is as follows:[30]. In this case, the casting is reheated to a temperature at which sufficient plastic flow can occur. When heated, the outside of the specimen is expanded before the centre becomes warm. Thus, the centre will be placed under an additional tensile stress, and its tensile strength will be increased.

CHAPTER-06

6. CONCLUSIONS

The following conclusions may be drawn from the results of the present investigation:

(1) The increased rate of cooling produced by chill casting increases the refinement/elimination of primary silicon crystal from the structure and hence improves the tensile properties and hardness of the Al-Si piston alloy. On the other hand, in slowly cooled sand casting, coarse plate like primary silicon including acicular type eutectic structure is observed resulting inferior properties.

(2) Strontium modification eliminates the primary silicon crystal and refines the eutectic structure from both chill and sand castings and hence improves the tensile properties and hardness of aluminium-silicon piston alloy.

(3) The percentage porosity of modified aluminium-silicon piston alloy is slightly higher for both rates of cooling, although the strength and hardness is improved due to structural modification.

(4) The fracture surface of the modified alloy seems to be ductile type, whereas brittle type fracture is noticed in the unmodified alloy.

(5) The full heat treatment (solution, ageing and precipitation treatment) increases the strength of the alloy at the expense of ductility for both the modified and unmodified alloy. However, the effect of heat treatment is more pronounced in

the sand cast specimens than the chill cast specimens.

(6) Very fine, equiaxed and globular type structures are obtained in the heat treated modified alloys indicating that modification has some effect on heat treatment operation.

(7) The residual stress in the modified alloy is found to be fully relieved due to thermal treatment, which satisfies the condition of static equilibrium. On the other hand, unmodified alloys show some degrees of residual stresses exist after heat treatment, indicating that further treatment or other procedure needs to be applied.

(8) Finally, for best combination of structure and properties in the aluminium-silicon piston alloy, modification together with full heat treatment is advocated.

SUGGESTIONS FOR FURTHER WORK

It is clear that there are a significant number of process variables that influence the structure and properties of aluminium-silicon piston alloy. It is hoped that this study has provided a frame work for understanding the effects of process variables on structure and properties and in doing so, it has highlighted the need for further work in the following area.

(1)   Solidification characteristics of aluminium-silicon piston alloys should be investigated.

(2)   Effect of process variables on tribological properties of the aluminium-silicon piston alloy should be made.

(3)   A comparative study of sodium and strontium modification on structure and properties of aluminium-silicon eutectic alloy should be carried out.

(4)   Effect of alloying elements on structure and properties of aluminium-silicon piston alloy should be investigated.

(5)   Attempt should be made to show the effect of thermal treatment parameters on residual stresses of aluminium-silicon piston alloy.

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