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PROPERTIES OF HYPEREUTECTIC ALUMINUM-SILICON ALLOYS PRODUCED BY POWDER METALLURGY TECHNIQUES

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PHYSICAL METALLURGY DIVISION

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C. F. Dixon* and H. M. Skelly**

SUMMARY OF RESULTS

Three hypereutectic aluminum-silicon alloys containing 25%, 35% and 45% Si were prepared using powder metallurgy techniques. Pre-alloyed powders, which were produced by atomization of the molten alloys, were fabricated by hot pressing and extruding to give material with density close to theoretical.

Metallographic examination of the powders showed that both atomization and melt additions contributed to refinement of the primary silicon.

The alloys were mechanically tested before and after various heat treatments and it was found that increasing the silicon content from 25% to 45% produced no significant change in tensile strength but lowered the ductility and increased the hardness.

The coefficient of thermal expansion of the alloys decreased with increasing silicon content.

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1. INTRODUCTION

Much work has been done in recent years on the development of hypereutectic aluminum-silicon casting alloys, primarily for use in the automotive industry(1-5). These alloys have low density, high strength-to-weight ratio, good wear resistance, and low coefficient of thermal expansion, but they suffer from the disadvantage that the primary silicon phase solidifies over a wide temperature range and forms large particles that tend to segregate, resulting in inferior mechanical properties and poor machinability. Significant refinement of the primary silicon phase has been obtained by the use of nucleation catalysts, improved melting practices, and fast freezing rates, but further refinement continues to be sought.

Consideration of the problem suggested that refined hypereutectic aluminum-silicon alloys might be made by powder metallurgy techniques. By using pre-alloyed atomized powder, not only could recommended melting practices and nucleation catalysts be used, but the rapid freezing rate of each powder particle would induce refinement of the primary silicon phase. Another attractive feature, unique to the powder metallurgy process, was that the size of the powder particles would itself be a limiting factor on the size of the primary silicon phase, and by sieving out the larger particles, powder fractions containing a fine dispersion of the silicon phase might be obtained.

This report describes the powder metallurgy techniques used to prepare some hypereutectic aluminum-silicon alloys. The properties obtained from such material are reported and discussed, and the alloys are compared with hypereutectic alloys prepared by conventional methods of melting and casting.

2. EXPERIMENTAL PROCEDURE

2.1 Alloy Powder Preparation

The materials used to prepare the pre-alloyed powders are listed in Table 1.

TABLE 1

Alloy Materials

Material	Purity	Source
Aluminum	99.99%	Aluminum Company of Canada Ltd.
Silicon	99.10%	Union Carbide Canada, Ltd.
Copper Brazing Rod	7% P	Canadian Liquid Air Co.
Magnesium	99.99%	Dominion Magnesium Ltd.

Three hypereutectic aluminum-silicon alloys were prepared with nominal silicon contents of 25%, 35% and 45%. Melting and alloying of the 800 g melts were carried out in zirconia-washed silicon carbide crucibles heated in a resistance furnace. In order to get the silicon to dissolve, the alloying temperature was raised with increasing silicon content, the Al-25% Si, Al-35% Si, and Al-45% Si melts being held at 825 °C (1520 °F), 930 °C (1705 °F) and 1200 °C (2190 °F), respectively, until alloying was complete. The melts were degassed with "Foseco" tablets*, and then 0.03% P (in the form of copper brazing rod) and 1.0% Mg were added to refine the primary silicon; this melt treatment is based on that found by other investigators(4) to be effective in refining the primary silicon phase. The melts were then skimmed, and poured at the above temperatures into an atomizing apparatus similar to an arrangement described elsewhere(6), except that it was modified so that water sprays, as well as jets of compressed air, atomized the stream of molten metal. This procedure was used in all cases except for one melt of the Al-25% Si composition, which was made without additions of phosphorus or magnesium.

The resulting powders were dried and sieved, and the -100 mesh fraction was retained for further processing.

2.2 Compacting and Extruding

The alloy powders were cold pressed at 30 tsi for 1 min into 2 in. diameter billets approximately 3 in. long. The cold pressed billets were wrapped in 0.010 in. thick stainless steel sheet to prevent galling and then hot pressed at 30 tsi and 350 to 400 °C (660 to 750 °F) for 10 min. The hot pressed billets were heated at 350 to 400 °C (660 to 750 °F) for 30 min and extruded through a die at 400 °C (750 °F) to 1/2 in. diameter rod (extrusion ratio 16:1).

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* A proprietary brand of degassing agent containing a chlorinated hydrocarbon.

The Al-25% Si and Al-35% Si alloy billets extruded without difficulty at 400 °C (750 °F) but the Al-45% Si alloy billets could not be extruded at this temperature, and all tests on the latter composition were done on the hot pressed material. It is possible that the Al-45% Si would extrude satisfactorily at some higher temperature.

2.3 Heat Treatment

The effect of heat treatment on the properties of the three alloys was investigated by heating them to 535 °C (1000 °F) for 6 hr and quenching into boiling water, followed by ageing at 200 °C (390 °F) for times of up to 4 hr. All heat treatments were carried out in air in a muffle furnace.

2.4 Mechanical Testing

Room temperature tensile tests were carried out on an Instron machine. The test specimens, which were machined to PMD Drawing No. 100, were 1 in. long and had a gauge length of 0.447 in. and a gauge diameter of 0.126 in. Brinell hardness surveys were carried out on all three compositions.

2.5 Thermal Expansion

The coefficient of thermal expansion between 20 °C (70 °F) and 300 °C (570 °F) was determined for the three alloys. The dilatometer specimens were 2.56 in. long by 0.312 in. diameter for the Al-25% Si and Al-35% Si alloys, and 1.57 in. long by 0.129 in. diameter for the Al-45% Si alloy.

2.6 Density

The densities of the alloys were determined in accordance with ASTM Designation B311-58, which is based on the displacement of water by the test specimen.

2.7 Metallography

Samples of the powders were mounted for microexamination by stirring them into a small quantity of Eastman 910 adhesive and then pouring the resulting mixture on to the grooved face of a blank bakelite mount. After allowing the adhesive to set at room temperature, the specimens were ready for polishing....

For microexamination, the specimens were ground on emery paper to 4/0 grit and then polished with Linde A compound on silk cloth and finally with Linde B compound on microcloth.

2.8 Chemical Analysis

Samples for chemical analysis were taken from the -100 mesh powder prior to cold pressing.

3. EXPERIMENTAL RESULTS

3.1 Alloy Composition

The results of the chemical analysis of the -100 mesh powders are listed in Table 2.

TABLE 2

Alloy Composition (Wt %)

Alloy	Si	P	Mg	Cu
Al-25% Si	24.5	0.007	1.04	0.36
Al-25% Si*	24.1	-	-	-
Al-35% Si	33.0	0.005	1.14	0.37
Al-45% Si	44.0	0.008	1.05	0.36

* No P, Mg, or Cu additions.

3.2 Silicon Refinement

The atomized powders were of irregular shape, and contained a wide range of particle sizes. Figures 1, 2 and 3 illustrate the size, shape and microstructure of the powders produced from the 25%, 35% and 45% Si alloys, to all of which phosphorus and magnesium had been added to refine the primary silicon phase. The primary silicon phase shows as grey particles. It can be seen that there is a slight increase in the size of the silicon particles with increasing silicon content, although the particles are fairly uniform in all cases and none of them is very big, even in the larger powder particles.

The 25% Si alloy powder that had no phosphorus or magnesium additions contained, in general, a fine dispersion of silicon, but the occasional large particle was present, as illustrated in Figure 4.

As already mentioned, only the -100 mesh fraction of the powders was processed and tested, and Figures 5, 6 and 7 illustrate the appearance of this fraction for the 25%, 35% and 45% Si compositions with refining additions. The 25% Si powder to which no refining additions were made was similar to Figure 5, the large silicon particles having been eliminated by sieving as they were present mainly in the alloy particles of +100 mesh size.

Figures 8, 9 and 10 illustrate the transverse microstructures of the 25%, 35% and 45% Si alloys, respectively, in the as-extruded condition (a small piece of extruded Al-45% Si alloy was available for microexamination). The silicon particle size is finer in the extruded material than in the -100 mesh powder, and the difference increases with the silicon content; the pressing and extruding apparently result in a further reduction in the size of the silicon particles. Figure 11 is a photomicrograph of the 45% Si alloy after hot pressing and it can be seen that the silicon particle size is finer than in the original powder (see Figure 7) but slightly coarser than in the extruded rod (see Figure 10). The microstructures of the extruded rods in the longitudinal direction were similar to those shown for the transverse direction.

Table 3 gives the size of the primary silicon particles in the extruded and (for 45% silicon only) hot pressed materials.

TABLE 3

Size of Primary Silicon Particles

Alloy	Condition	Average Size of Coarser Particles (Microns)	Size of Largest Particles (Microns)
Al-25% Si	As-extruded	5	17
Al-35% Si	As-extruded	5	17
Al-45% Si	As-extruded	5	20
Al-45% Si	Hot pressed	10	50

None of the photomicrographs shows the presence of eutectic, but this was a result of the polishing and photographic techniques which were designed to bring out the primary silicon clearly. Etching showed that the eutectic was present in refined condition in all alloy powders.

3.3. Heat Treatment and Mechanical Properties

The effect of heat treatment on the hardness of the alloys is shown by the results listed in Table 4.

TABLE 4

Effect of Heat Treatment on Brinell Hardness* (500 kg load)

Alloy	Condition	Heat Treated 535 °C (1000 °F) for 6 hr then Aged at 200 °C (400 °F) for following times (hr):					
		0	1/2	1	1-1/2	2	4
	As-extruded						
Al-25% Si	86	58	59.5	62.5	62.5	60.5	59
Al-25% Si**	65	41	40.5	45	38	36.5	39
Al-35% Si	67	56	57	65	58	57	54.5
	As hot pressed						
Al-45% Si	114	121	134	127	117	-	113

* At least two determinations per condition

** No refining additions.

The results of the room temperature tensile tests are tabulated in Table 5 and plotted in Figure 12. Most of the tensile results listed in Table 5 are the averages of three tests, but where this is not the case the actual number of tests is given in brackets. The Brinell hardness results listed in Table 5 were carried out on sections adjacent to the tensile specimens, and the values given are the averages of at least two determinations.

TABLE 5

Mechanical Properties at Room Temperature

Alloy	Condition*	UTS (kpsi)	0.2% YS (kpsi)	% El $4\sqrt{A}$	BHN (500 kg/30 sec)
Al-25% Si	As-extruded	33.2	22.5	8	86
Al-25% Si	H.T.Aged 200 °C (400 °F) 1 hr	31.9	30.1	2	60.5
Al-25% Si	H.T.Aged 200 °C (400 °F) 4 hr	32.2	30.2	2	63
Al-25% Si**	H.T.Aged 200 °C (400 °F) 1 hr	21.4	14.3	6	41
Al-25% Si**	H.T.Aged 200 °C (400 °F) 4 hr	21.5	15.8	6	43
Al-35% Si	As-extruded	32.1(1)	31.3(1)	2(1)	67
Al-35% Si	H.T.Aged 200 °C (400 °F) 1 hr	32.0(2)	30.8(2)	2(2)	61
Al-35% Si	H.T.Aged 200 °C (400 °F) 4 hr	29.0	ND	0	64.6
Al-45% Si	Hot pressed	39.9(2)	ND	0(2)	114
Al-45% Si	H.T.Aged 200 °C (400 °F) 1/2 hr	28.1	ND	0	132
Al-45% Si	H.T.Aged 200 °C (400 °F) 4 hr	33.7(2)	ND	0(2)	126

* H.T. = Heat treated at 535 °C (1000 °F) for 6 hr then quenched into boiling water.

** No refining additions.

ND Not determined.

3.4 Thermal Expansion

The results of the thermal expansion coefficient measurements are listed in Table 6, which also includes, for comparison purposes, values quoted elsewhere for Al-21% Si(4); Al-5% Si(7) and Al-12% Si(7) casting alloys and for cast iron(8).

TABLE 6

Thermal Expansion Coefficients for Al-Si Alloys and Cast Iron

Alloy	Coefficient (in./in./°C x 10^6)	Temperature Range
Al-25% Si	17.44	20-300°C (70-570°F)
Al-35% Si	15.23	" "
Al-45% Si	14.51	" "
Al-21% Si (4)	17.89	0-300°C (32-570°F)
Al-21% Si (4)	18.94	" "
Al- 5% Si (7)	24.0	20-300°C (70-570°F)
Al-12% Si (7)	21.5	" "
Cast Iron (8)	11.5-12.7	20-400°C (70-750°F)

The results listed in Table 6 are plotted in Figure 13 to show the relationship between silicon content and coefficient of thermal expansion. The silicon percentages plotted in Figure 13 are the chemical analysis values.

3.5 Density

The results of the density determinations carried out on the Al-25% Si and Al-35% Si extruded rods, and the Al-45% Si hot-pressed billet are given in Table 7.

TABLE 7

Density of Al-Si Alloys

Alloy	Density (g/cc)
Al-25% Si	2.60
Al-35% Si	2.50
Al-45% Si	2.48

These values are marked in Figure 14, which is a plot of "theoretical" density versus silicon content obtained by joining the two points corresponding to the densities of 100% Al (2.70 g/cc) and 100% Si (2.33 g/cc). As in Figure 13, the percentage silicon values are the chemical analysis results.

4. DISCUSSION

As mentioned in the "Introduction", an inherent advantage of the powder metallurgy technique as applied to production of hypereutectic aluminum-silicon alloys is that the fineness of the alloy powder is a factor which can control the size of the particles of primary silicon.

Another advantage of the powder metallurgy process is that parts can be pressed to the desired size and shape with little or no subsequent machining. In the present work, most of the evaluation and testing were done on extruded material but the results of the tests on the hot-pressed Al-45% Si alloy indicate that useful properties can be obtained by hot pressing alone. The latter method would be advantageous for producing to shape small components in which light weight, wear resistance, and low thermal expansion are desirable.

A disadvantage of the powder process is that the size of the component that can be manufactured is limited by the press capacity, but larger presses are being put into operation in the powder metallurgy industry.

4.1 Silicon Refinement

The main purpose of this investigation was to study the effect of the rapid cooling produced by atomization of the molten metal on the size and distribution of the primary silicon phase in hypereutectic aluminum-silicon alloys. The melting practice used in preparing all melts (except one Al-25% Si alloy melt) was based on that used by Urdea and Telang(4) to refine the primary silicon.

It is generally considered that the phosphorus reacts with the melt to form aluminum phosphide (AlP) which provides numerous crystallization nuclei for the primary silicon during solidification, and the beneficial effect of chlorine is attributed to its action in fluxing out undesirable impurities that might reduce the effectiveness of the AlP in providing crystallization nuclei. The magnesium addition is thought to promote refinement of the silicon by being absorbed on the surface of the growing silicon crystallites, thus curtailing their growth rate but increasing the rate of nucleation.

In each of the powders made, the silicon primary phase was refined, as shown by the photomicrographs, Figures 1 to 4. However, comparison of the microstructures of Al-25% Si with refining additions (Figure 1) and without refining additions (Figure 4) shows that the former contains the finer and more uniform silicon particles, indicating that, although the atomizing process itself effects considerable refinement of the silicon, further refinement results from the melt additions. Comparison of Figures 1, 2 and 3 also shows that the silicon particle size increases with silicon content and that the oblong particles become more numerous as the silicon content increases.

Separation of the -100 mesh fraction of the powders resulted in further refinement as most of the larger silicon particles were present in the +100 mesh powder fraction; this result can be seen by comparing Figures 1, 2 and 3 with Figures 5, 6 and 7 respectively. Consolidation and extrusion of the powders resulted in further reduction in the size of the primary silicon (see Figures 8 to 11).

Although the particle size of the primary silicon is very fine in all of the extruded alloys, especially considering the high silicon content, it is possible that even more refinement might be accomplished by improving the alloying technique so as to increase phosphorus recovery, which appears to be related to the efficiency of the refining process; thus, Urdea and Telang(4) decreased the size of the primary silicon particles by a factor of four in chill-cast Al-21% Si alloy by increasing the phosphorus recovery from 20% to 90%. An even more drastic cooling of the molten metal during atomization might result in further refinement of the silicon.

Separation of a finer powder fraction by sieving is another possible method for obtaining a fine silicon particle size. The results of the chemical analysis of the -100 mesh powders (see Table 2) show that the silicon contents were close to the required compositions, indicating that at this powder size there was no significant change in the silicon content due to sieving out of particles containing unrefined primary silicon.

4.2 Heat Treatment and Mechanical Properties

The alloys showed very little response to heat treatment, which is perhaps surprising in view of their composition, except in the case of the Al-25% Si alloy which contained no refining additions. Addition of more copper, or other alloying elements, would improve the strength of the alloys and render them more responsive to heat treatment.

The bar-graph (Figure 12) shows that there was little difference between the tensile strengths of the alloys after different heat treatments, except in the case of the Al-45% Si alloy, which showed a drop in tensile strength after ageing for 1/2 hr, but the reason for this is not known.

The comparatively low strength of the Al-25% Si alloy (without additions) is due to the absence of magnesium and copper. Poor ductility was exhibited by all alloys except Al-25% Si, with additions, in the as-extruded condition, and Al-25% Si, without additions.

Increasing the silicon content from 25% to 45% had little effect on the tensile properties apart from a lowering of the ductility.

4.3 Thermal Expansion

As Figure 13 shows, increasing the silicon content of aluminum-silicon alloys results in a steady decrease in the coefficient of thermal expansion, it being about 25% less for the 45% Si alloy than for a 21% Si casting alloy. From the graph, an alloy with a silicon content of 58% should have about the same coefficient as cast iron.

4.4. Density

Assuming that the straight line joining the densities of aluminum and silicon in Figure 14 represents the theoretical densities of aluminum-silicon alloys, then it can be seen that the Al-25% Si alloy has about 100% density, whereas the Al-35% Si and Al-45% Si alloys are slightly less than full theoretical density, being 97% and 98% respectively. These results are confirmed by the appearance of the microstructures of these compositions (see Figures 8, 9 and 10). The copper and magnesium would of course affect the density of the aluminum-silicon alloys.

4.5 Machinability

No machining tests were carried out on the alloys, but they machined satisfactorily during preparation of the dilatometer and tensile specimens. Figure 15 is a photograph of a tensile specimen machined from the Al-45% Si alloy.

5. CONCLUSIONS

1. Refined aluminum-silicon alloys with up to 45% Si can be produced by powder metallurgy methods.

2. Atomization of the Al-25% Si alloy results in a considerable degree of refinement of the primary silicon phase.

3. Increasing the silicon content from 25% to 45% produces no significant change in tensile strength, but lowers the ductility and increases the hardness.

4. The coefficient of thermal expansion is progressively decreased with increasing silicon content, and the Al-45% Si alloy has a thermal expansion about 25% less than that of the Al-21% casting alloy.

5. Densities close to theoretical can be obtained by hot compaction and extrusion of hypereutectic aluminum-silicon alloys.

6. Hypereutectic aluminum-silicon alloys produced by powder metallurgy techniques have good machinability.

6. FUTURE WORK

The following are some aspects of the this work that merit further investigation:

a) A more detailed study of the influence of melt additions on refinement of the primary silicon in the atomized powder would be of interest. It is possible that refining additions are not necessary for low silicon alloys but that in the case of the high silicon alloys efficient use of refiners will refine the silicon even in the larger particles of powder, making it unnecessary to sieve out the large particle fraction.

b) A more drastic quenching of the molten metal during atomization might refine the silicon sufficiently to eliminate the necessity of adding refiners to the melt.

c) Elimination of the extrusion step in the fabrication procedure would be an advantage and it is possible that hot pressing alone would produce satisfactory material.

d) It would be of interest to determine the wear resistance of the aluminum-silicon alloys produced by the powder metallurgy technique and to compare it with the wear resistance of cast aluminum-silicon alloys and other materials.

e) Application of the technique described in the report to other alloy systems.

ACKNOWLEDGEMENTS

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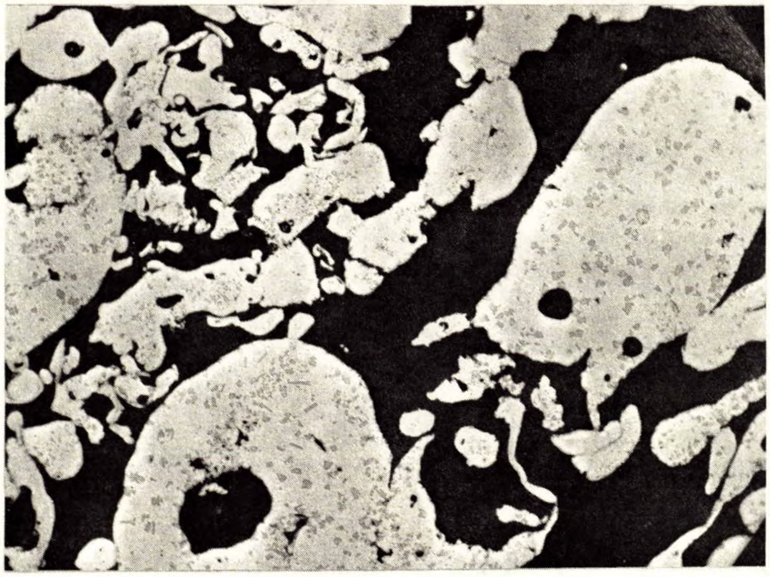
X100
Figure 1. Al-25% Si Powder. (Before sieving).

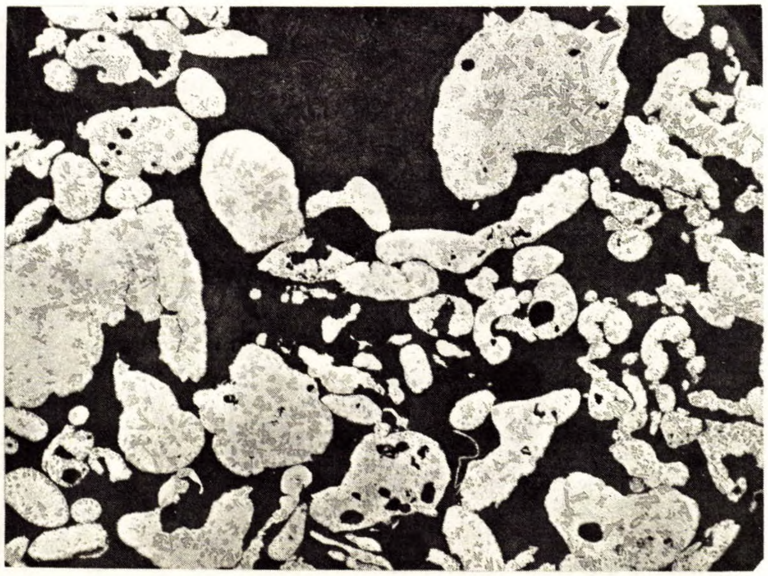
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Figure 2. Al-35% Si Powder. (Before sieving).

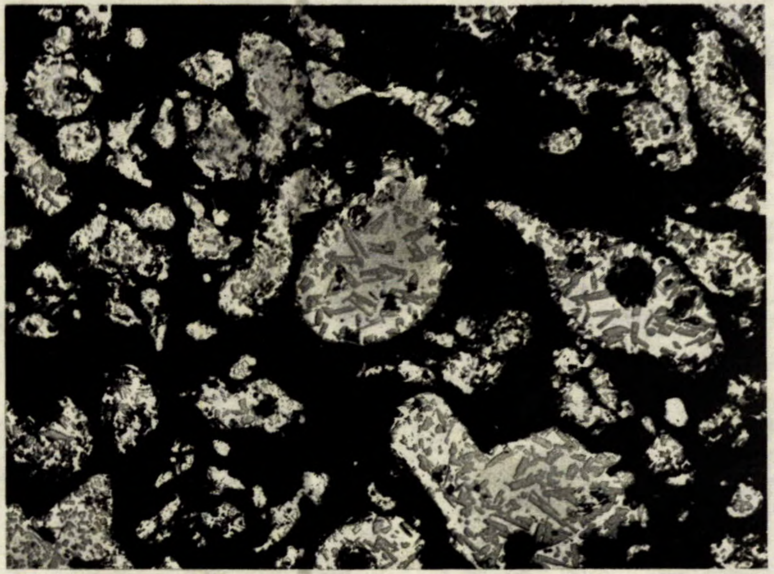

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Figure 3. Al-45% Si Powder. (Before sieving).

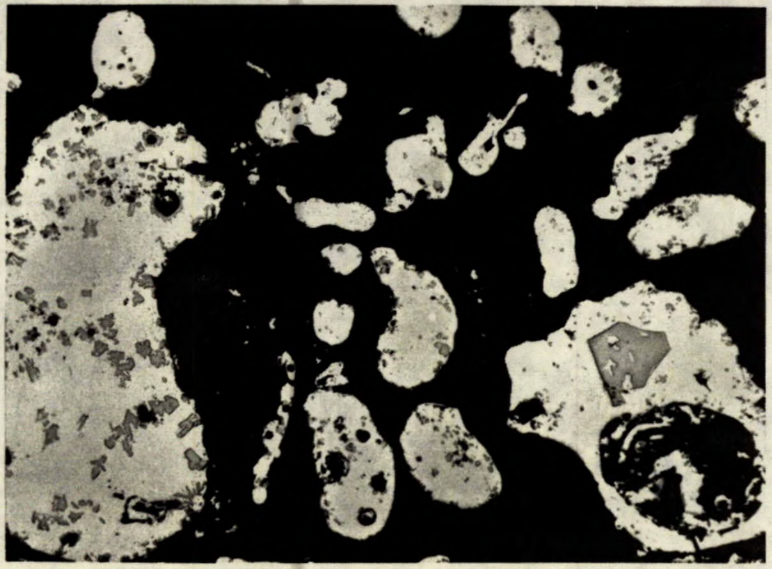

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Figure 4. Al-25% Si Powder. No refining additions.
(Before sieving).

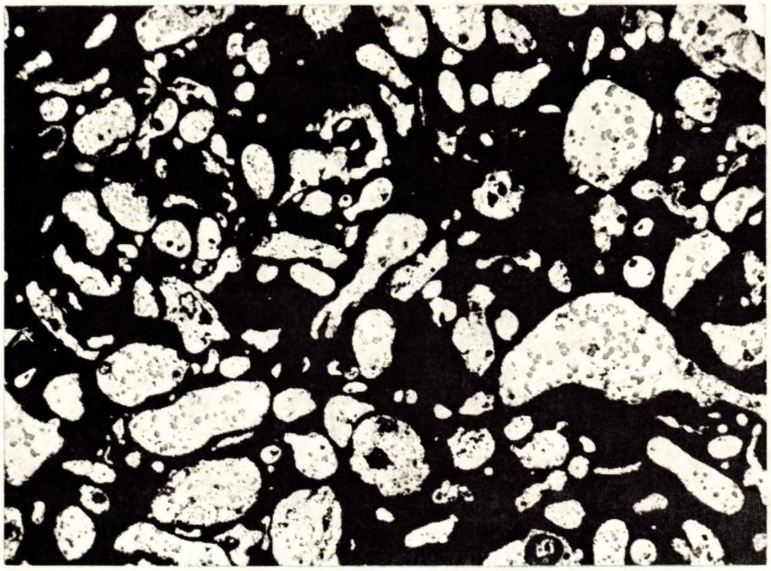

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Figure 5. Al-25% Si Powder, -100 mesh.

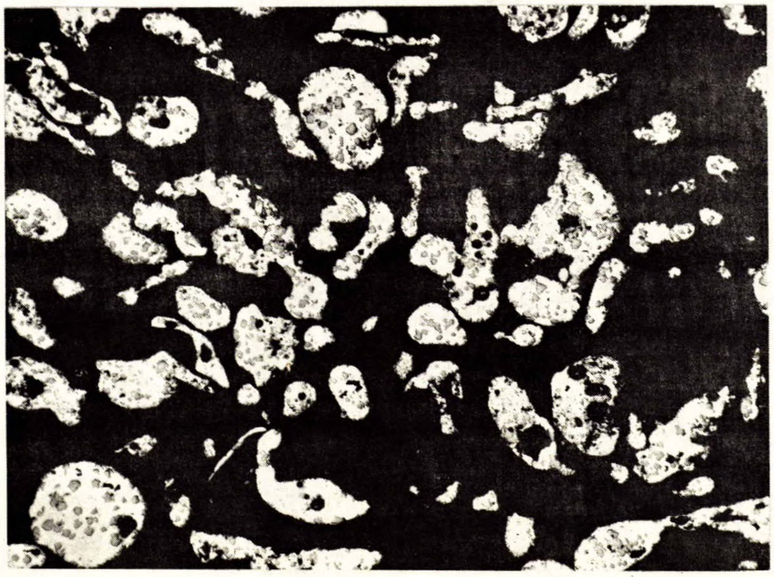

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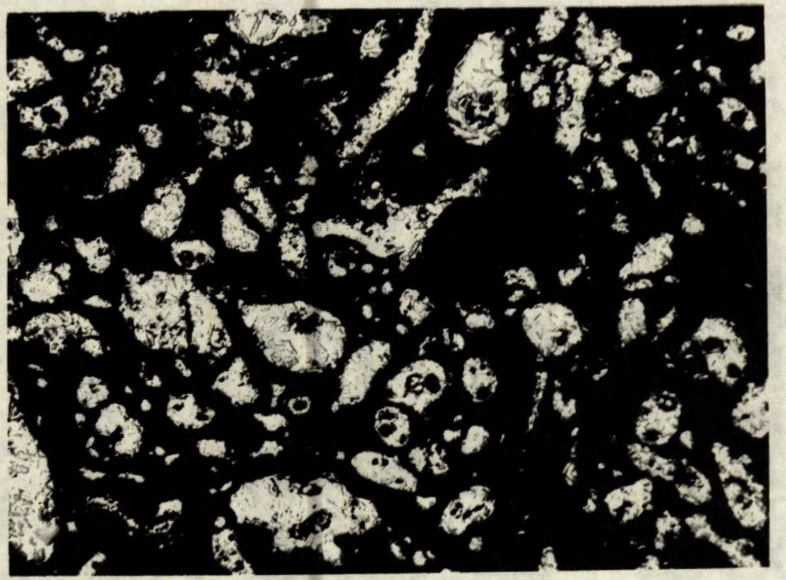
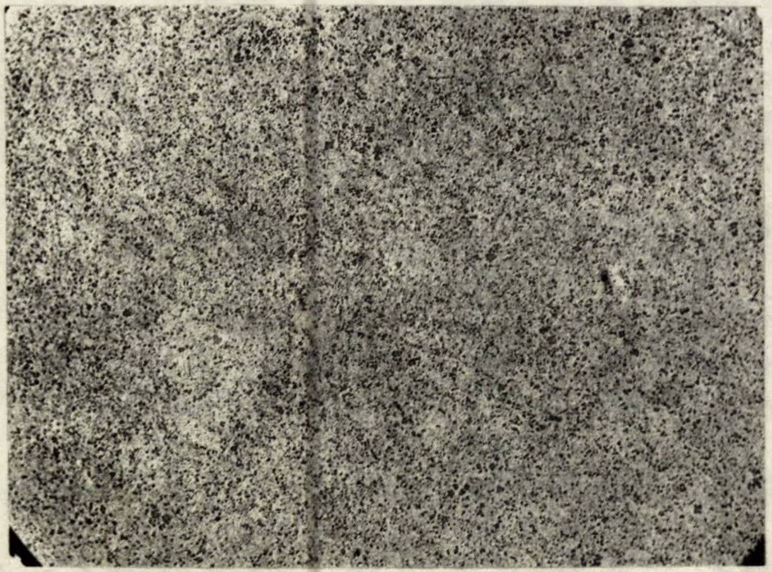
Figure 6. Al-35% Si Powder, -100 mesh.



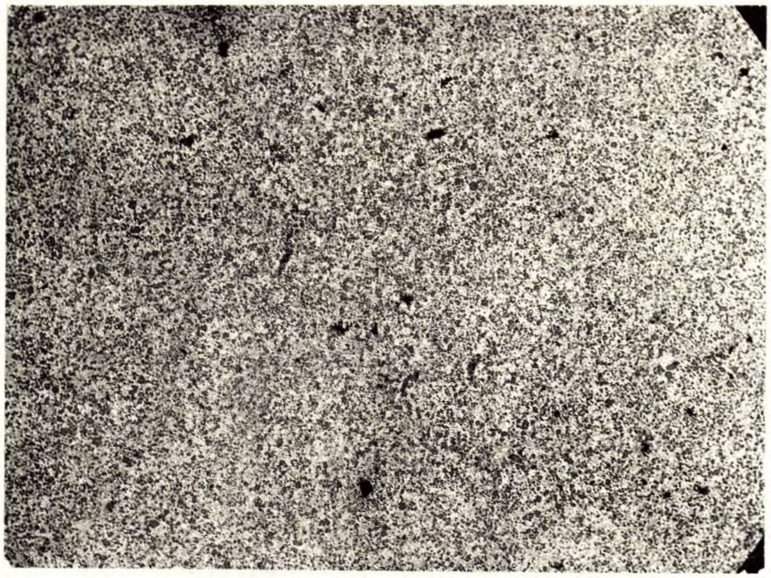
X100

Figure 7. Al-45% Si Powder, -100 mesh.



X100

Figure 8. Al-25% Si Extruded Rod. (Transverse section).



X100

Figure 9. Al-35% Si Extruded Rod. (Transverse section).

X100

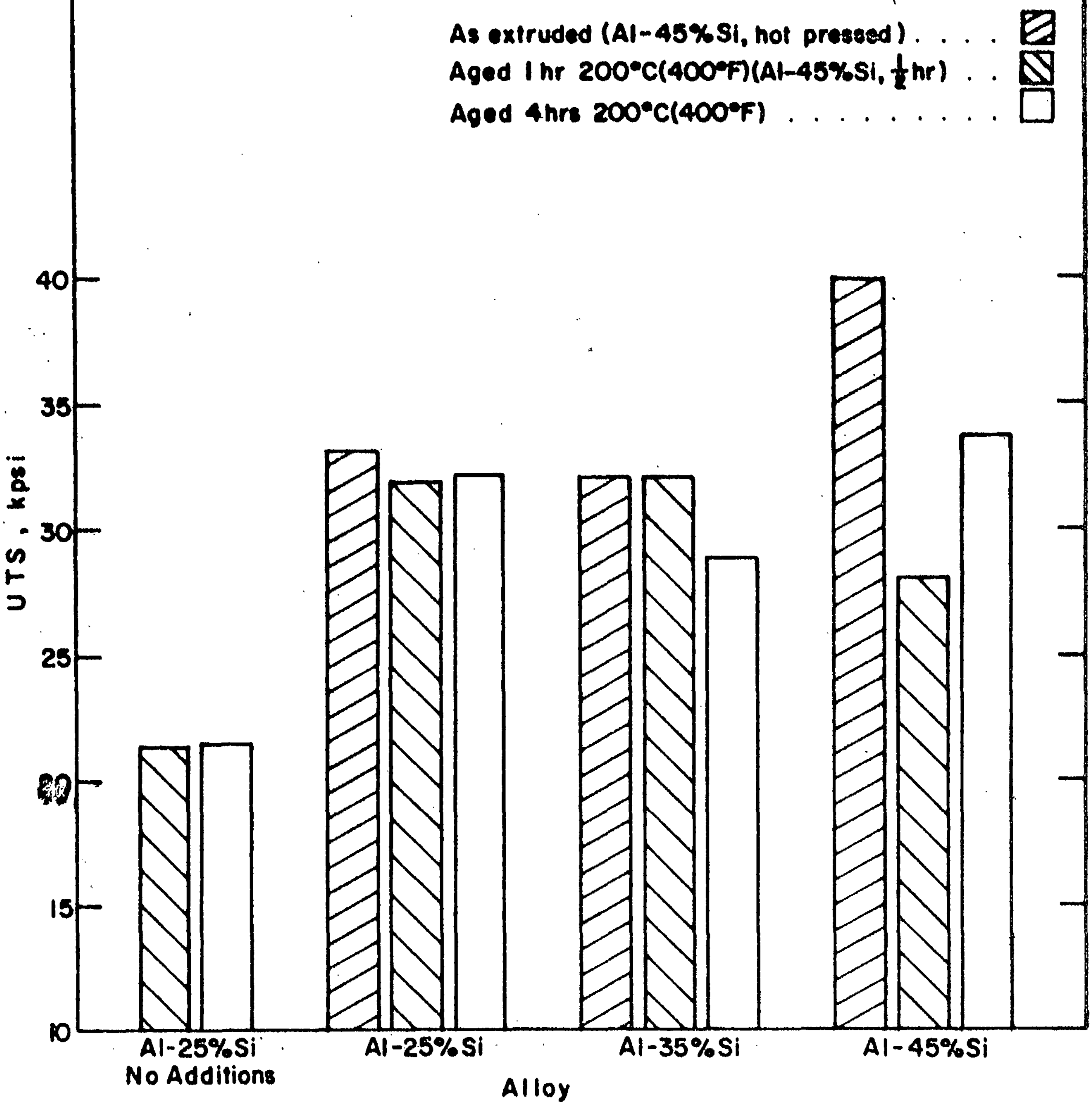
Figure 10. Al-45% Extruded Rod. (Transverse section).

X100

Figure 11. Al-45% Si Hot Pressed Billet.

FIGURE 12: TENSILE STRENGTH OF ALUMINUM-SILICON ALLOYS

Heat treated at 535°C (1000°C) for 6 hours then aged at 200°C(400°F)



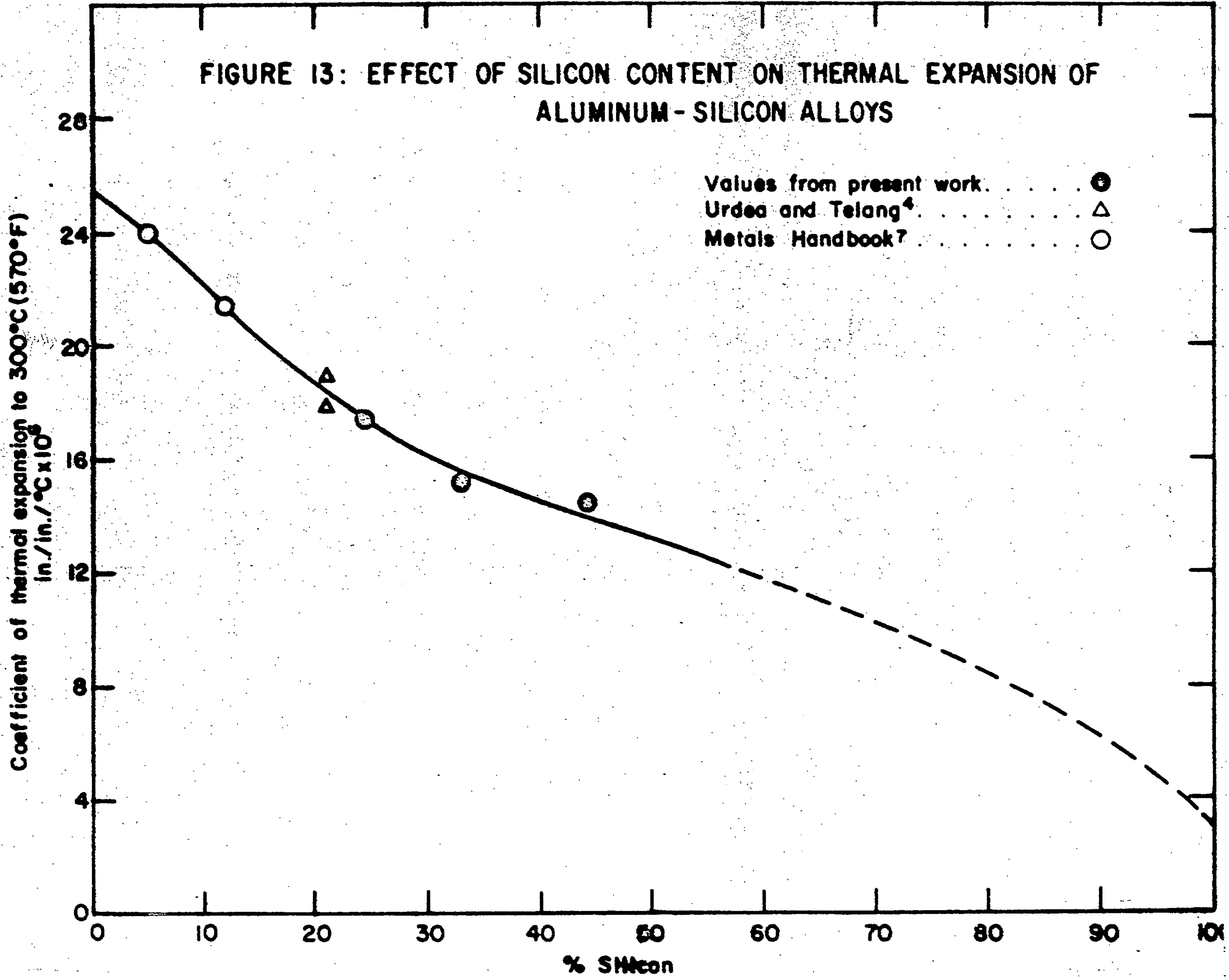


FIGURE 13: EFFECT OF SILICON CONTENT ON THERMAL EXPANSION OF ALUMINUM-SILICON ALLOYS

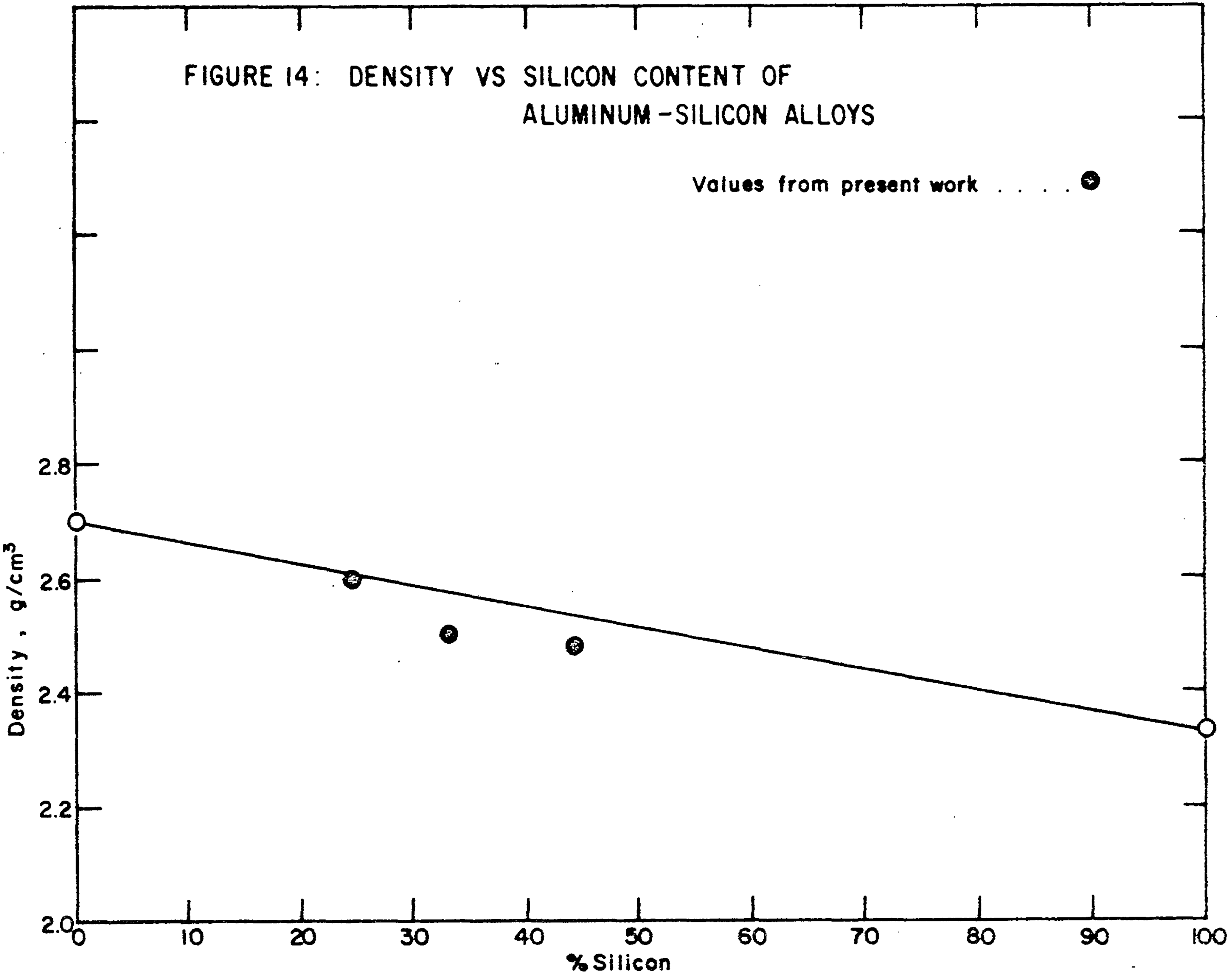
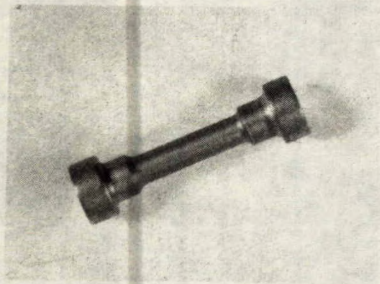


FIGURE 14: DENSITY VS SILICON CONTENT OF ALUMINUM-SILICON ALLOYS



X1.25

Figure 15. Al-45% Si Alloy.
Tensile Test Specimen.