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HYPEREUTECTIC ALUMINUM-SILICON ALLOYS PRODUCED BY HOT COMPACTION OF ATOMIZED POWDER

H.M. SKELLY AND C.F. DIXON

PHYSICAL METALLURGY DIVISION

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HYPEREUTECTIC ALUMINUM-SILICON ALLOYS PRODUCED BY HOT COMPACTION OF ATOMIZED POWDER

by

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

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ABSTRACT

The main objects of this investigation were: (1) to determine whether a fine dispersion of primary silicon phase could be obtained in hypereutectic aluminum-silicon atomized powder without adding nucleation catalysts to the melt; (2) to determine whether the atomized powders could be consolidated by hot pressing.

Atomized powders of Al-25% Si, Al-35% Si and Al-45% Si alloys containing a fine dispersion of silicon were successfully produced without the use of nucleation catalysts. The powders were consolidated to densities close to theoretical by hot pressing at temperatures of 400°C (750°F) and 550°C (1020°F) and pressures of 38,000 psi and 81,000 psi.

Some properties of the powders and of the compacts produced from them were determined.

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Direction des mines

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ALLIAGES HYPEREUTECTIQUES D'ALUMINIUM ET DE SILICIUM OBTENUS PAR COMPRESSION À CHAUD DE POUDRE ATOMISÉE

par

H. M. Skelly* et S. F. Dixon**

RÉSUMÉ

Les buts principaux des recherches étaient 1) de déterminer la possibilité d'obtenir une dispersion de fines particules de silicium primaire dans une poudre atomisée d'aluminium et de silicium sans addition de catalyseurs de nucléation au bain; et 2) de déterminer si les poudres atomisées peuvent être agglomérées par compression à chaud.

Des poudres atomisées d'alliages Al-25% Si, Al-35% Si et Al-45% Si contenant une dispersion de fines particules de silicium ont été obtenues sans l'aide de catalyseurs de nucléation. Les poudres ont été consolidées à des densités à peu près idéales par compression à chaud à des températures de 400°C (750°F) et de 550°C (1020°F) et à des pressions de 38,000 et de 81,000 livres au pouce carré.

Les auteurs ont aussi déterminé quelques-unes des propriétés des poudres et des comprimés obtenus.

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1. INTRODUCTION

Hypereutectic aluminum-silicon casting alloys are of interest because of their low density, high strength-to-weight ratio, good wear resistance, and low coefficient of thermal expansion. However, these cast alloys suffer from the disadvantage that the primary silicon forms large particles that tend to segregate on solidification, resulting in low mechanical properties and poor machinability. Some refinement of the primary silicon phase has been achieved in casting alloys containing up to 25% silicon, by adding to the melt nucleation catalysts such as sodium and phosphorus, and by casting thin sections in chill moulds.

In previous work (1) it was shown that refined hypereutectic aluminum-silicon alloys containing up to 45% silicon could be produced by powder metallurgy techniques. The pre-alloyed powders were produced by atomization of the molten alloys to which phosphorus and magnesium were added as refiners. The atomized powders were consolidated by cold pressing, followed by hot pressing and then extruding.

The purpose of the work reported here was to examine the possibility of producing a fine dispersion of primary silicon hypereutectic aluminum-silicon alloys by atomization alone (i.e. without the addition of any refining agents to the melt) and also to determine the feasibility of consolidating the resulting powders by hot pressing alone.

2. EXPERIMENTAL PROCEDURE

2.1 Preparation of Alloy Powders

The materials used to prepare the pre-alloyed hypereutectic aluminum-silicon powders were 99.99% pure aluminum obtained from the Aluminum Company of Canada, Limited, and 99.1% pure silicon obtained from Union Carbide Canada Limited.

Three alloy powders, with nominal compositions of 25% Si, 35% Si and 45% Si, were prepared. Melting and alloying were carried out in a silicon-carbide crucible heated by a gas-fired furnace. To dissolve the silicon, the melts were heated to 900°C (1650°F), 1050°C (1920°F) and 1200°C (2190°F) for the Al-25% Si, Al-35% and Al-45% Si alloys, respectively. After degassing with chlorine, and skimming, the melts were reheated to the above temperatures and poured into an atomizing apparatus similar to that described elsewhere [2].

After drying, the atomized powders were screened and the +100 mesh fraction was discarded. To obtain a sufficient quantity of powder it was necessary to prepare at least two melts of each alloy, and to ensure a homogeneous product the respective alloy powders from different melts were blended in a twin-shell laboratory blender.

2.2 Examination and Testing of Powders

Samples of the powders were mounted for microexamination by stirring them into Eastman 910 adhesive and then pouring the resulting mixture onto the grooved face of a bakelite mount. After allowing the adhesive to set at room temperature, the specimens were polished. The specimens were first 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.

The screen analysis of the powders was determined in accordance with Metal Powders Industries Federation (MPIF) Standard 5-62.

The apparent density and flow rate were determined in accordance with MPIF Standards 4-45 and 3-45, respectively, using the Hall Flowmeter funnel.

Each batch of powder was analysed chemically for silicon, and the Al-35% Si batch was also analysed for oxygen.

2.3 Hot Pressing

Prior to being hot pressed, the three alloy powders were isostatically pressed at 10,000 psi for 5 min to give compacts measuring 1-5/16 in. diameter by 3-1/4 in. long. The compression ratio during this operation was 1.4 to 1. For hot pressing, the compacts were reduced in size, by grinding, to 1-3/16 in. diameter by 2-1/2 in. long.

Hot pressing was carried out in a heated alloy steel die having 1-1/4 in. diameter bore, the temperature of the die being determined with a chromel-alumel thermocouple. Each isostatically-compressed compact was wrapped in 0.005 in. stainless steel foil before insertion in the die, to prevent galling.

The hot pressing details are given in Table 1. Three different combinations of temperature and pressure were investigated, namely 400°C (750°F) at 38,000 psi, 550°C (1020°F) at 38,000 psi, and 550°C (1020°F) at 81,000 psi. The compacts prepared at 400°C (750°F) and 38,000 psi (AD, AB and AC in Table 1) were heated in the die for 30 min before applying the load for 10 min. For the other compacts listed in Table 1, the load was applied as soon as the sample had been inserted into the die and was held for 15 min.

Compacts AI and AK were in the hot die longer than 15 min because some difficulty was experienced in removing them after compaction.

The compression ratio during hot compaction was 1.5 to 1, so that the total compression ratio from uncompacted powder to hot-pressed compact was 2.1 to 1.

2.4 Examination and Testing of Compacts

Specimens from each compact were polished for microexamination, using the same polishing procedure as described above for the powders.

Room-temperature tensile tests and Vickers hardness measurements were carried out on specimens machined from each compact.

The density of specimens machined from the compacts was determined according to ASTM Designation B311-58, based on water displacement.

3. RESULTS AND DISCUSSION

3.1 Properties of Powders

Figures 1, 2 and 3 are photomicrographs which illustrate the microstructure of each alloy powder. The primary silicon phase shows as dark grey particles within each powder grain. In each case the silicon is fine and uniformly distributed, although the average size of the particles does increase with increasing silicon content.

The results of the screen analyses on the three lots of powder are given in Table 2. Over 50% of each powder was in the -100 to +200 range, and the remainder was distributed quite uniformly in the -200 mesh ranges except for the 35% Si alloy, which contained an appreciably higher percentage of -325 meshpowder than did the other two powders. A small fraction of +100 mesh material was found to be present in each batch.

The apparent densities and flow rates of the three powders are listed in Table 3. The apparent density values are the averages of three determinations, all of which were in good agreement. As expected, the apparent density decreases as the silicon content increases.

The flow rate figures showed a high degree of scatter, and the values given in Table 3 are the averages of 9 or 12 determinations. The scatter in the flow rate values was probably related to the comparatively long times taken by the powders to flow through the Hall Flowmeter funnel. The flow rate decreased as the silicon content increased.

MPIF Standard 3-45 for the determination of flow rate requires that a constant weight (50 g) of sample be used in the test. Thus, when the powder is very light, as in the case of the aluminum-silicon powders, a 50g sample represents a comparatively large volume of powder. Conversely, if the powder is heavy, 50 g occupies a small volume. The apparent density of the powder can thus have a significant effect on the flow rate value. It would appear that a more realistic measure of flow rate would be obtained by basing it on a constant volume of sample rather than on constant weight. This would have more significance for practical application because, in powder metallurgy production, dies are filled with a constant volume rather than constant weight of powder. However, the compactibility of the powder is also important in production, because the greater the compaction ratio the more powder is required to obtain a compact of given size.

Chemical analysis of the -100 mesh powders gave values of 24.0% Si, 32.6% Si and 42.5% Si for the three alloys, indicating some loss of silicon during alloying.

Inert gas fusion analysis for oxygen in the 35% Si (nominal) powder gave a value of 0.14%, equivalent to 0.3% Al_2O_3.

3.2 Properties of Compacts

There were no significant differences in the microstructures of the compacts prepared using three different hot pressing conditions. Figures 4, 5 and 6 are photomicrographs showing representative structures for the three alloys. It can be seen that there is very little porosity in the samples. The size of the primary silicon phase increases with increasing silicon content, corresponding to the microstructure of the powders. The powder particles appeared to have bonded equally well, irrespective of the hot pressing conditions. There was no evidence of growth of the silicon particles during hot pressing, and the size of the particles compares favourably with that in Al-25% Si alloy castings produced with melt refining additions and cast into thin chilled sections.

The results of the tensile and hardness tests are listed in Table 4. The alloys exhibited low ductility and, as is usual with such material, it was difficult to obtain accurate tensile values. All the values obtained for the Al-35% Si powder that had been hot pressed at 550°C (1020°F) and 38,000 psi were obviously too low to be representative of the material and are not included in Table 4.

A comparison of the tensile properties of the same compositions prepared under different hot pressing conditions shows that hot compaction at

550°C (1020°F) and 38,000 psi gave higher properties than did hot compaction at 400°C (750°F) and 38,000 psi. Also, there was no improvement in the properties of the compacts prepared at 550°C (1020°F) when the pressure was increased from 38,000 psi to 81,000 psi. The results also show that the tensile strength increases with silicon content.

The earlier work [1] included tensile tests on Al-25% Si alloy (with no refining additions to the melt) that had been extruded after hot compaction. The average tensile properties for that material were: UTS, 21.4 kpsi; 0.2% YS, 15.0 kpsi; elongation, 6%. The results given in Table 4 for Al-25% Si hot pressed at 550°C (1020°F) and 38,000 psi compare favourably with those values.

The hardness values follow the expected trend; that is, they increase with silicon content. For each silicon content, the compacts prepared at 400°C (750°F) have significantly higher hardness than those prepared at 550°C (1020°F); this difference is thought to be due to an annealing effect resulting from the higher compaction temperature.

The density values for the compacts (see Table 5) are all close to theoretical. There is no significant difference between the densities of the same alloy compacted under different conditions. As in the case of the powders, the density decreases with increasing silicon content.

In order to determine whether there was any variation in density within the hot-pressed compact, five discs (1/2 in. diameter by 3/16 in. thick) were machined from an Al-25% Si compact that had been pressed at 550°C (1020°F) and 38,000 psi, and their densities were determined. The values obtained were 2.56, 2.55, 2.59, 2.57 and 2.57 g/cc, showing substantial uniformity from top to bottom of the compact. Usually a single-action die, such as the one employed in this work, gives non-uniform density when used to press deep compacts. The uniform density of the Al-25% Si compact probably occurred because the high temperature of compaction made the alloy sufficiently soft to be able to transmit the applied pressure to all parts of the compact.

The compression ratios from loose powder to hot-pressed compact, calculated from the densities given in Tables 3 and 5, are as follows:

Al-25% Si	:	2.4 to 1
Al-35% Si	:	2.7 to 1
Al-45% Si	:	3.0 to 1

These ratios are higher than the ratio of 2.1 to 1 given on page 3 because they are based on the density of untamped powder (apparent density) whereas the 2.1 value was calculated from the volume of powder that had been tamped into a tube prior to isostatic pressing.

4. CONCLUSIONS

1. Atomization of Al-Si alloys containing up to 45% Si is sufficient to refine the silicon primary phase without the addition of refiners to the melt.

2. Atomized powders of hypereutectic Al-Si alloys can be compacted by hot pressing.

3. Densities close to theoretical can be obtained by hot compaction of hypereutectic Al-Si alloys.

4. Increasing the compacting temperature from 400°C (750°F) to 550°C (1020°F) improves the room-temperature tensile properties of the compacts, but no improvement is evident when the compacting pressure is increased from 38,000 psi to 81,000 psi.

5. It is recommended that, for future work, compaction be carried out at 550°C (1020°F) and 38,000 psi.

5. FUTURE WORK

Further work will be done in an effort to improve the strength and ductility of the alloys.

6. ACKNOWLEDGEMENTS

Thanks are extended to the Analytical Chemistry Subdivision of the Mineral Sciences Division for carrying out the chemical analyses.

7. REFERENCES

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2. C.F. Dixon and T.E. Davis - "An Apparatus for the Production of Fine Metal Powders" - Physical Metallurgy Division Internal Report PM-I-60-10, Mines Branch, Department of Mines and Technical Surveys, Ottawa (1960).

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HMS:CFD:(PES)LC

TABLE 1

Hot Pressing Details

Compact Ident.	Alloy	Compacting Temp., °C (°F)	Compacting Pressure (psi)	Compacting Time (min)	Total Time in Hot Die (min)
AD	25% Si	400 (750)	38,000	10	40
AB	35% Si	"	"	"	"
AC	45% Si	"	"	"	"
AE	25% Si	550 (1020)	38,000	15	15
AH	25% Si	"	"	"	"
AF	35% Si	"	"	"	"
AG	45% Si	"	"	"	"
AI	25% Si	550 (1020)	81,000	15	25
AJ	35% Si	"	"	"	15
AK	45% Si	"	"	"	40

TABLE 2

Sieve Analyses of -100 Mesh Powders

U.S. Sieve No.		Weight %		
		25% Si	35% Si	45% Si
	+ 80	-	-	-
- 80	+ 100	1.9	1.9	3.1
- 100	+ 140	37.1	32.3	39.0
- 140	+ 200	20.3	18.2	21.2
- 200	+ 230	11.3	10.8	11.4
- 230	+ 325	12.6	13.5	11.7
- 325		16.8	23.3	13.6

TABLE 3

Apparent Density and Flow Rate of -100 Mesh Powders

Alloy	Apparent Density (g/cc)	Flow Rate (sec/50g)
25% Si	1.06	86.8
35% Si	0.95	104.5
45% Si	0.83	117.2

TABLE 4

Tensile Properties and Hardness of Hot-Pressed Al-Si Alloy Powders*

Alloy	Hot Pressing Conditions		Tensile Properties			VHN (5 kg load)
			UTS (kpsi)	0.2% YS (kpsi)	% El $4\sqrt{A}$	
25% Si **	400°C (750°F)	38,000 psi	11.6	None	1	79 (6)
25% Si	550°C (1020°F)	38,000 psi	22.5 (1)	16.5 (1)	3 (1)	56 (4)
25% Si	550°C (1020°F)	81,000 psi	17.6	15.1	3	66 (5)
35% Si **	400°C (750°F)	38,000 psi	13.4	None	0	99 (6)
35% Si	550°C (1020°F)	38,000 psi	-	-	-	72 (3)
35% Si	550°C (1020°F)	81,000 psi	25.6 (2)	23.9 (2)	2 (2)	80 (4)
45% Si **	400°C (750°F)	38,000 psi	14.3 (2)	None (2)	0 (2)	126 (6)
45% Si	550°C (1020°F)	38,000 psi	27.5	None	2	114 (4)
45% Si	550°C (1020°F)	81,000 psi	27.7	None	3	114 (4)

* Each value is average of 3 tests, except where indicated otherwise by numbers in brackets.
** Tensile specimens machined to PMD Drawing No. 100, with 0.126 in. gauge diameter; all other specimens machined to PMD Drawing No. 44, with 0.178 in. gauge diameter.

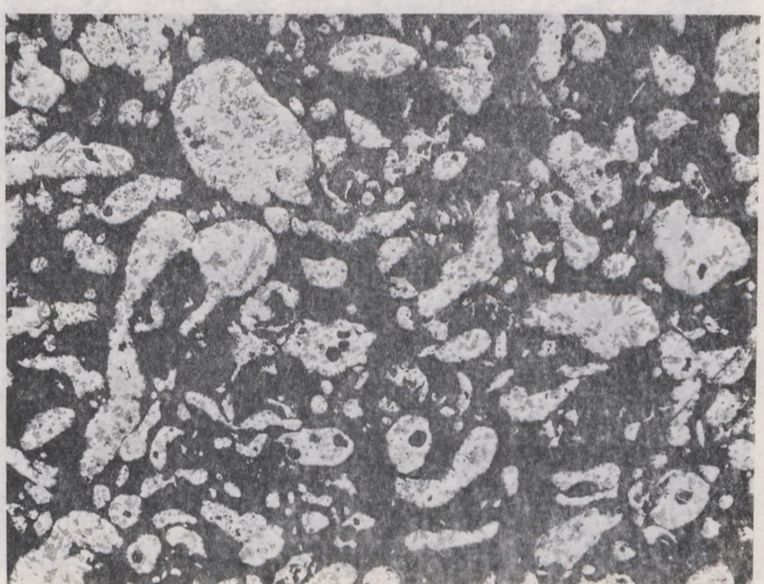
TABLE 5

Densities of Hot-Pressed Al-Si Alloy Powders

Alloy	Hot Pressing Conditions		Density (g/cc)
25% Si	400°C (750°F)	38,000 psi	2.59
"	550°C (1020°F)	38,000 psi	2.60
"	550°C (1020°F)	81,000 psi	2.53
35% Si	440°C (750°F)	38,000 psi	2.55
"	550°C (1020°F)	38,000 psi	2.51
"	550°C (1020°F)	81,000 psi	2.54
45% Si	400°C (750°F)	38,000 psi	2.49
"	550°C (1020°F)	38,000 psi	2.51
"	550°C (1020°F)	81,000 psi	2.51

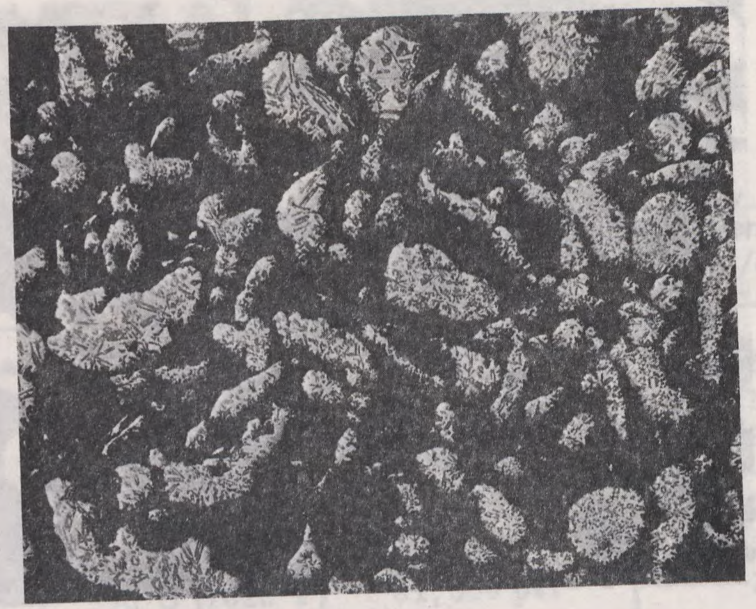
X100

Figure 1 - Al-25% Si alloy powder, -100 mesh.



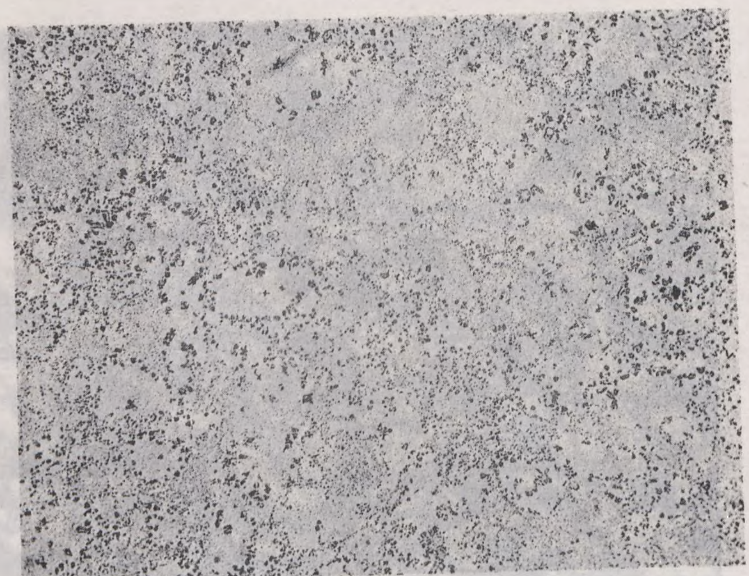
X100

Figure 2 - Al-35% Si alloy powder, -100 mesh.



X100

Figure 3 - Al-45% Si alloy powder, -100 mesh.

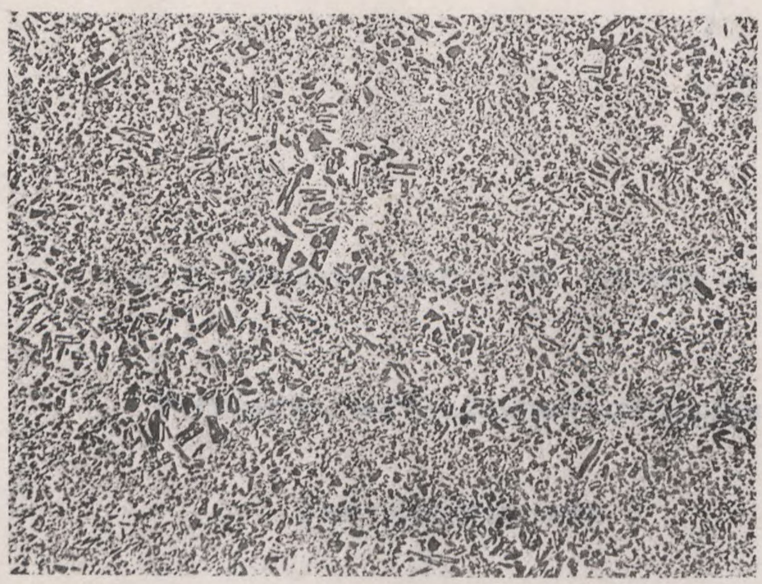


X100

Figure 4 - Hot compacted Al-25% Si alloy powder.

X100

Figure 5 - Hot compacted Al-35% Si alloy powder.



X100

Figure 6 - Hot compacted Al-45% Si alloy powder.