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DEVELOPMENT OF HIGH-STRENGTH AND HIGHLY DUCTILE HYPO-EUTECTIC Al-Si ALLOYS BY NANO-REFINING THE CONSTITUENT PHASES

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Abstract

Among the structural light weight materials, Al-Si alloys can be the most widely used Al-alloys for aerospace and automotive applications. Our recent experiments using Ba additions of 1-3wt% into the melt of hypo- and hyper-eutectic Al-Si alloys have shown considerable promise in terms of both Si refinement of nano-scale (verified with both by SEM and TEM studies) and limited mechanical testing. The preliminary experiments indicate that the solidification conditions together with the new hypothesis of Si refinement can be successfully used with permanent mold casting. Recent permanent mold casting of such Al-8%Si-1.8%Ba hypo-eutectic Al-Si alloys have resulted cast alloys that without any further processing revealed a microstructure in which eutectic silicon assumes nano-fibrous morphology and where the primary aluminium phase shows dendrites of very fine size. The alloys in as cast conditions exhibit UTS values of around 172 Mpa and ductility values of about 15%.

Introduction

Alloys-developing organizations related to industries such as aerospace, automotive and defense (manufacturers of armor and structural components in military weaponry systems) face ever-increasing demands to reduce weight and fuel costs. Cast hypo-eutectic Al-Si alloys containing a very fine morphology silicon phase uniformly distributed in the matrix of the aluminum phase can meet these demands. In an Al-Si binary system [1] as shown in Figure 1, the hypo-eutectic range exists for a silicon composition that is lower than 12.2 at% (12.7 wt%) of silicon. In the microstructure of hypo-eutectic Al-Si alloys, two major components coexist, the primary and the eutectic phase. The primary phase consists of Al containing about 1.67% Si as solid solution that exists in the form of dendrites, while the eutectic structure consists of an aluminum-rich solid solution of silicon and virtually pure silicon and that is found in between the arms of the primary Al dendrites.

It is well known that the presence of highly-refined components in an alloy invariably leads to improved strength and ductility. As established in numerous publications[2,3], this refinement of the silicon content by a trace addition of impurities such as Na and Sr into the melt of Al-Si based lightweight alloys follows this principle. However, the impurity-added Al-Si based light alloys such as A3XX.0 and A4XXX.0 [4] developed so far in as-cast condition seldom have yielded an ultimate tensile stress (UTS) in excess of 200 MPa. The primary reason for not obtaining more improved mechanical properties than that just mentioned is that the silicon phase in these cast alloys is not sufficiently refined to offer a very high UTS value.

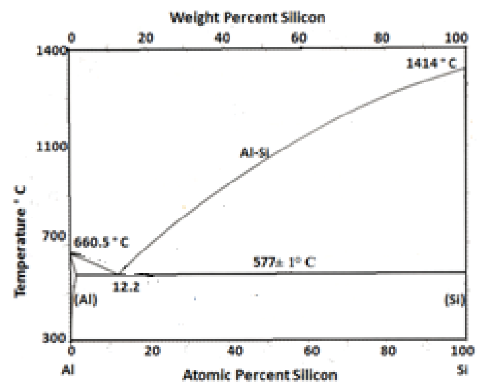

Figure 1. Al-Si phase diagram [1].

In order to improve the mechanical properties of these as-cast alloys heat treatment is required, but the heat treatment is not cost effective. Thus a method must be developed by which silicon morphology in the base Al-Si hypereutectic alloys can be refined to a nano-scale level that can render a high strength in access of 250 MPa and a ductility of around 15% in as-cast condition. A determination of such base Al-Si alloys then can be used as starting materials to develop more ultra high strength light weight Al- Si alloys by various heat treatment processing.

Recently, based upon the concept of the solubility of barium (Ba) metal in the silicon phase Shamsuzzoha and his coauthors [5-7] have demonstrated that hyper-eutectic alloys containing up to 17-wt% Si can be produced by directional solidifications without a primary silicon phase being present in the microstructure. The procedure, which alloys, has resulted in a shift to the normal eutectic point from 12.7 wt% to 17wt% Si (Figure 2). The silicon in these alloys appears as nano- and close-to-nano-size fibers at high growth rate (2500μm/sec) and moderate growth rate

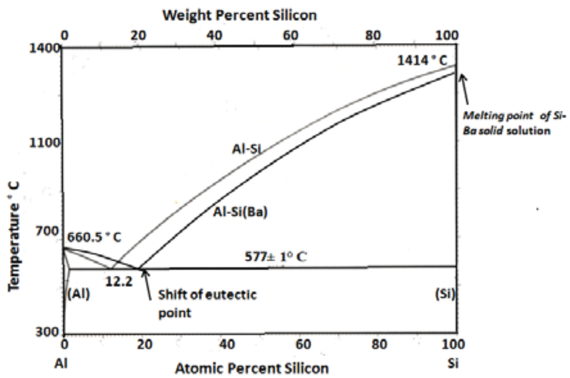

Figure 2. Schematic representation of the liquid-solid tie lines and a shift of eutectic point due to solid solution of Ba in Si as imposed in the Al-Si phase diagram**.**

(250μm/sec) respectively involves the addition of Ba into a melt of hyper-eutectic Similar treatment in the shape casting of the hyper eutectic Al-17-wt% Si alloy also revealed [8] a microstructure in which Si phase assumes a close to nano-sized flake morphology silicon. The same concept has now been applied to develop high strength and highly ductile hypo-eutectic Al-Si alloys by shape castings. This paper deals with the development of shape castings that produce high strength and highly ductile hypo-eutectic aluminium (Al)-silicon (Si) alloys with silicon content in the range of 6-9% and that possess nano-sized fibrous silicon morphology and a refined Al dendrites in the microstructure.

Experimental Procedures

The process involves the melting of an alloy that has a composition of Al-8%Si in an argon-rich environment. The furnace used for melting is a resistance furnace, in which temperature is kept to 750ºC for Ba treatment. After Ba treatment the resulting melt was poured into one of the risers of a standard ASTM B-108 mold with the intention to characterize the coupon from the opposite side only. This pouring technique can be considered as a bottom pouring technique. The mold temperature during pouring of the melt was preheated at 400º F(204ºC); after pouring, the mold was allowed to cool down to room temperature. Longitudinal and transverse section specimens taken from near the center of the grown samples were used to determine the microstructure and mechanical testing. The microstructure of the alloy was investigated using a JOEL JSM-7000F SEM.

Result and Discussions

The microstructure of the alloys could not be well-resolved by optical microscopy. Hence samples of the alloys were deep etched and then investigated by scanning electron microscopy to study the morphology of silicon and aluminium phases. Energy dispersive x-ray spectrometry equipped with the SEM for the alloy showed an overall composition that is close to that of Al-8 wt% Si.

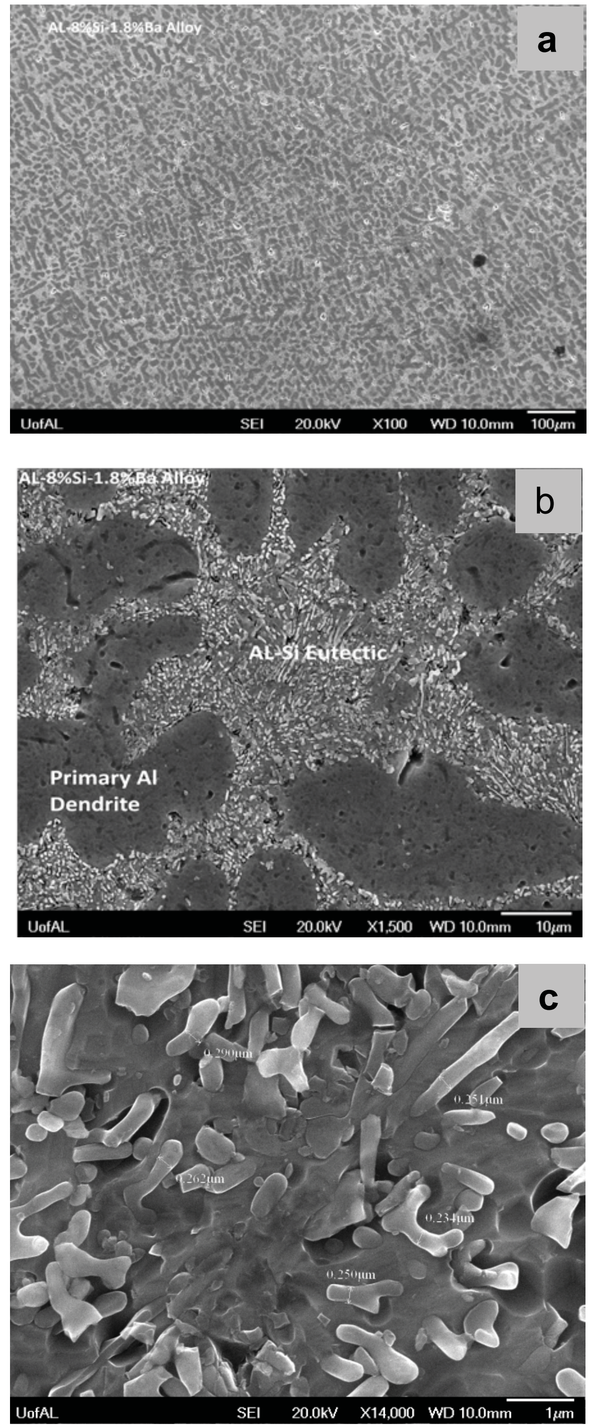

Figure 3. SEM micrographs of a deep etched shape cast Al-8% Si-1.8% Ba alloy (a) low magnification view resolving only primary Al dendrites in the microstructure, (b) high magnification view exhibiting flake/fibrous morphology for silicon phase, (c) showing the width of individual Si flakes /fibers to be nanometer in scale.

Figure 3a shows a SEM micrograph of a typical microstructure found in a resulting cast alloy. The eutectic phases appear dark in the microstructure as they not resolved. The primary aluminium phase appearing as whitish color dendrites shows a very refined morphology. Simple quantitative metallographic examination performed on the microstructure of the micrograph reveals that the amount of primary Al dendrites in these alloys is larger than that expected from a Ba-free Al-8%Si alloy. This is expected with addition of Ba, which causes eutectic point to shift towards higher Si content [7]. The same examination always revealed that the microstructure has only two type of constituent particles namely, the primary aluminum, and the eutectic of aluminium and silicon and no other phases. The microstructure shows no evidence of over-modification in the form of local coarsening and increasing of the inter-silicon spacing, which are usually found in those Al-Si alloys that are modified by excessive amount (above 0.5%) Sr [9].

The higher magnification micrograph of the alloy, as shown in Figure 3(b), reveals that the eutectic silicon phase assumes flake/ fibrous morphology in the microstructure. The eutectic silicon crystals found in the microstructure of the alloy follow a wheat sheaf growth pattern originating from a point of origin as can be seen from the center of the inter-dendritic region located at the center of the micrograph of Figure 3b. The diverging tendency from an origin for the growth pattern of flake/fiber-type silicon crystals is also evident in micrograph. The width of the eutectic silicon as in the microstructure assumes (Figure3c) nanometer in scale, which is at least 5 times finer than other Al-7 to10 %Si alloys that are refined by Sr or other impurity elements [10-11].

The very refined Si particle and the presence of more primary dendrites in these Al-8%Si-1.8%Ba alloys suggest that the alloys are likely to exhibit marked improvements in physical and mechanical properties over the existing hypereutectic Al-8 wt% Si alloys grown by similar shape casting. The tensile tests were therefore performed on the present as cast Al-8%Si-1.8%Ba

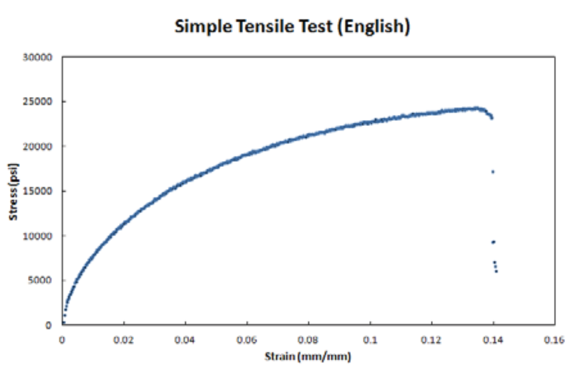

Figure 4. A stress vs strain plot for the Al-8%Si-1.8%Ba alloy.

A stress vs strain plot of a sample from Al-8%Si-1.8%Ba alloy is shown in Figure 4. These tensile tests yielded an average UTS value of around 165(5) MPa and elongation of around 15(2)% in as cast condition. These values are higher than those obtained from other similarly cast light weight Al-Si alloys [4].

Conclusion

The microstructure of the presently developed shape-cast high-strength cast hype-eutectic Al-Si alloy discussed in this paper reveals that the entire silicon content of the alloy appears uniform in size and assumes nano flake/fibrous morphology. The primary Aluminium phase in the microstructure is also very refined compared to other as cast light weight Al-Si alloys Appearances of such morphology of silicon and primary Al in the alloy can be attributed to the crystallization behavior of silicon that has Ba in the form of solid solution. It appears that the solid solution of Ba in silicon effects the crystallization of both the primary Al and eutectic silicon in the solidification of shape cast hypo-eutectic Al-Si alloy. The effect allows the hypo-eutectic melt to nucleate eutectic silicon and primary Aluminium crystal that after growth assume nano-meter and micro-meter in size respectively and resulted in development of a high strength and highly ductile alloys.

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