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Authors' Reply to Reply of Discussion on "Nucleation Mechanism of Eutectic Phases in Aluminum-Silicon Hypoeutectic Alloys"

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Communications

Reply to Discussion on "Nucleation Mechanism of Eutectic Phases in Aluminum-Silicon Hypoeutectic Alloys"*

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Shankar *et al*. published an article on the nucleation mechanism of the eutectic phases in Al-Si alloys in *Acta Materialia*[1] and republished some of the material in *Metall. Mater. Trans. A*.[2] They emphasized the role of Fe-rich β particles in initiating eutectic solidification in Al-Si alloys. In a discussion,[3] we objected to their proposal that each eutectic Si plate is nucleated by a β particle. They have now replied[4] to our discussion claiming that they did not state or imply that *all* the eutectic Si plates nucleate on β particles. They now state that the β phase *initiates* the nucleation event of eutectic Si. Once Si has nucleated at a specific location, it grows into the interdendritic eutectic liquid and further nucleation of Si occurs epitaxially on the solid eutectic Si phase. It thus seems that they now propose that only the first Si plate in a eutectic colony is nucleated by a β particle.

We do not believe that we misunderstood their previous publications. Figure 2 in their first article[1] shows a schematic of how each one of a series of β particles in front of an Al dendrite nucleates a Si particle, which develops as a separate plate growing into the liquid. After having presented their proposal of the role of β particles, they stated that "The following sections substantiate this mechanism of nucleation . . . ". One of those sections is Section III–D,[1] where they start by referring to previous suggestions that β particles could be a nucleant for eutectic Si in Al-Si alloys and then they present micrographs in Figure 7[1] stating that: "Almost every eutectic silicon flake in the microstructure has a β particle attached to its edge." It does not seem possible to reconcile those micrographs and that statement with their new statement that the β phase only initiates the nucleation event of the eutectic Si and that further nucleation of Si occurs epitaxially on the solid eutectic Si. It should further be emphasized that the title of their article was "Nucleation Mechanism of the Eutectic Phases in Aluminum-Silicon Hypoeutectic Alloys." Even in their Reply[4] to our Discussion[3] they emphasize that their article "addressed the nucleation aspects and not the growth aspects of the eutectic reaction."

The importance they attach to their Figure 7[1] is emphasized by the fact that in their second article,[2] they published it again (Figure 4) and again in their Reply[4] as Figure 2. Actually, all but one of the figures in the Reply are republications from the first article.

Furthermore, if they really believed that only the initial eutectic Si was caused by a β particle, the very extensive experimental study would seem meaningless. How can one hope to catch that minute β particle by inspecting sections through a bulk sample without even looking for the specific location from where the eutectic colony started?

We are happy to note that they now accept that β particles do not play a major role in the nucleation of the large number of Si plates that are found in a eutectic colony. We should mention that we interpret all those β particles observed in the old Figure 7 (now Figure 2) as precipitated on the Al/Si interfaces *after* the completion of the binary Al-Si eutectic reaction.

Therefore, we believe that the Al-Si eutectic in these alloys initiates on other potent nuclei for silicon present in the alloys, such as AlP. We have seen no convincing evidence that the β phase plays a role in initiating the formation of eutectic colonies at any common iron levels in these alloys, but we do not deny that Fe may have some effect on the development of a eutectic colony, including any constitutional effects from segregation.

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*S. Shankar, Y.W. Riddle, and M.M. Makhlouf: *Metall. Mater. Trans. A*, 2005, vol. 36A, pp. 1613-17.

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S. SHANKAR and M.M. MAKHLOUF

Dahle and Hillert point to three issues that they have with our Reply[1] to their Discussion.[2] First, they question the statement "Almost every Si flake in the microstructure has a β-(Al,Si,Fe) particle attached to its edge" and also Figure 7,[3] and they claim that it does not seem possible to reconcile the micrograph and the statement with the fact that the β phase only *initiates* the nucleation event of eutectic Si and that further nucleation of Si occurs epitaxially on the solid eutectic Si. Second, they ask "How can one hope to catch that minute β particle by inspecting sections through a bulk sample."

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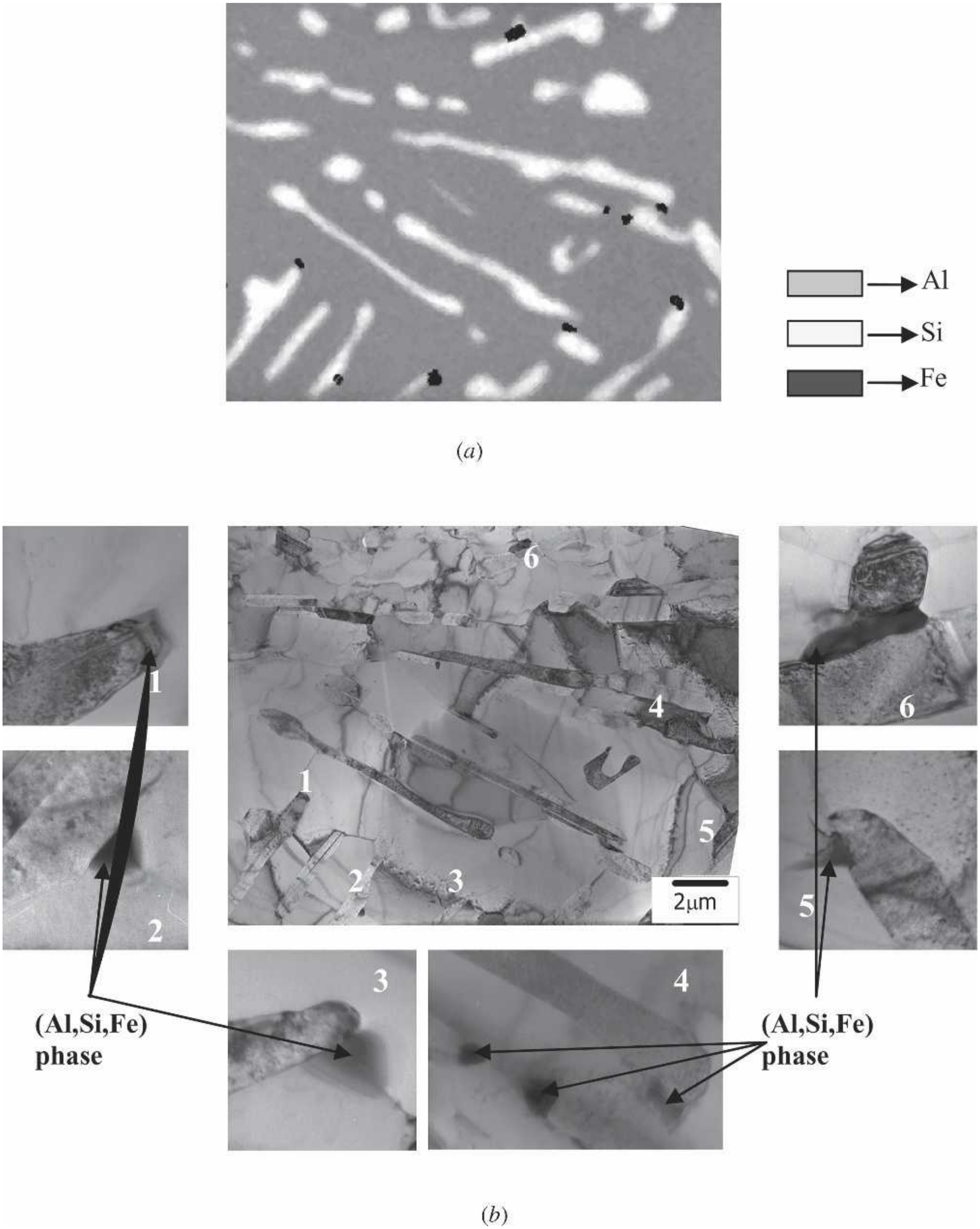

Fig. 1—Image showing association of the β-(Al,Si,Fe) phase with eutectic silicon: (*a*) Composite elemental map of Al, Si, and Fe obtained from the image shown in (*b*); (*b*) TEM bright field image showing locations where β-(Al,Si,Fe) particles were found [3].

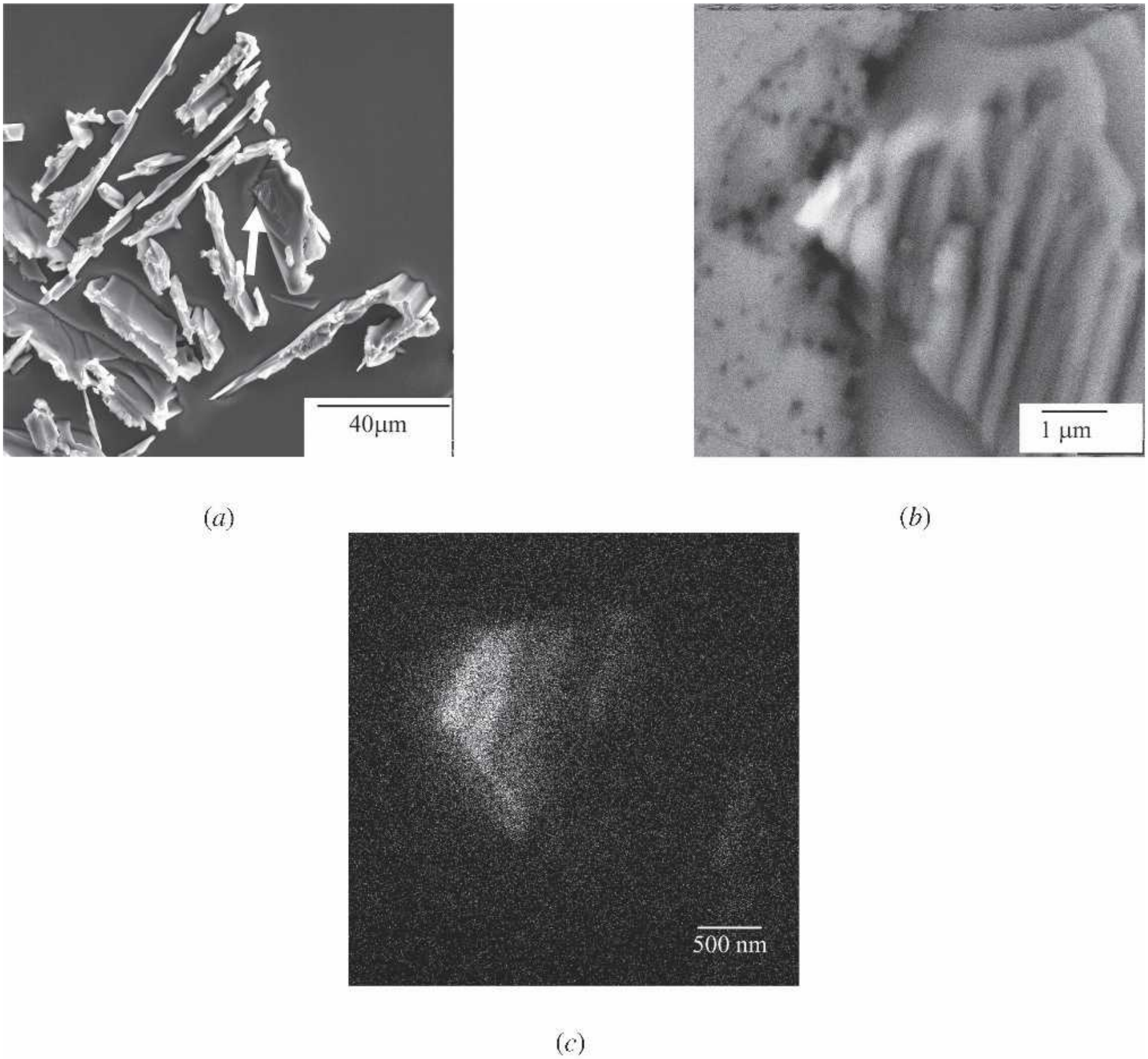

Fig. 2—SEM micrographs of Al-4.5 pct Si alloy: (*a*) secondary electron image; (*b*) Backscattered electron image of region indicated by the arrow in (*a*); (*c*) Elemental map of Fe highlighting the β-(Al,Si,Fe) precipitate [3].

Table I. Composition of (Al,Si,Fe) Particles Similar to That in Figure 2[3]

	Particle 1		Particle 2		Particle 3		Particle 4		Particle 5	
Element	Wt Pct	At. Pct	Wt Pct	At. Pct	Wt Pct	At. Pct	Wt Pct	At. Pct	Wt Pct	At. Pct
Al	63.64	73.66	62.8	69.2	62.83	72.98	64.59	74.58	61.53	70.95
Si	10.86	12.08	12.43	15.42	11.10	12.39	10.26	11.38	13.82	15.31
Fe	25.49	14.26	24.77	15.38	26.07	14.63	25.15	14.03	24.65	13.73

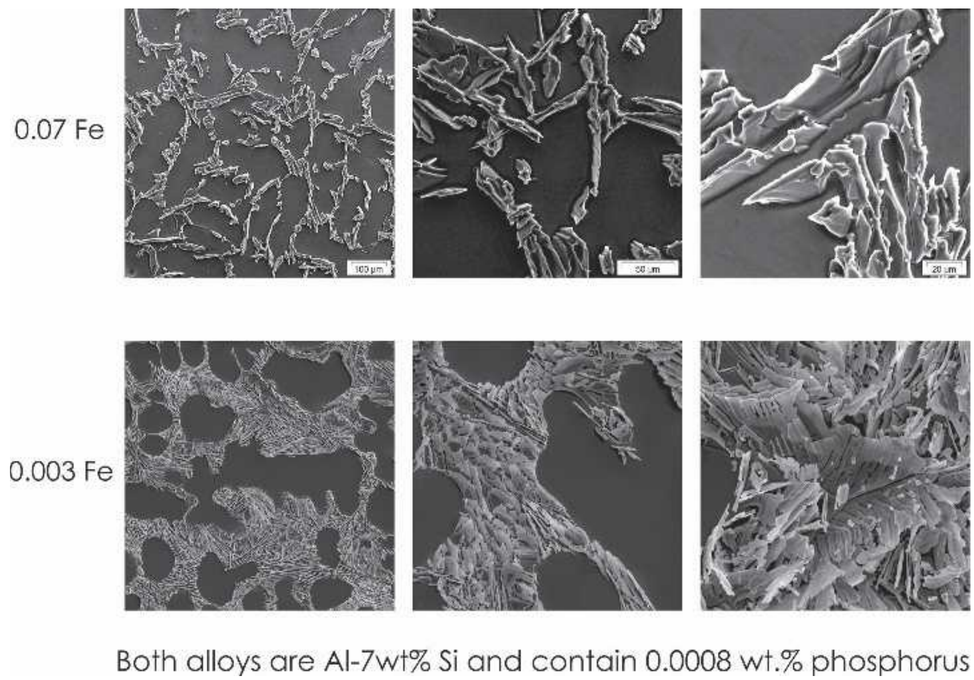

Fig. 3—Effect of iron and phosphorus on the morphology of eutectic silicon in Al-Si hypoeutectic alloys. Micron markers on the images of the top row apply to the corresponding images of the bottom row.

Third, they express their satisfaction that we "now accept that β particles do not play a major role in the nucleation of the large number of Si plates that are found in a eutectic colony."

We shall address each of these points separately in the following paragraphs.

Regarding the first point, Dahle and Hillert's objection to the content of our theory as presented in Reference 3 has to do with the language used to describe Figure 7; specifically, with our statement "*Almost* every Si flake in the microstructure has a β-(Al,Si,Fe) particle attached to its edge." Figure 1 is a reproduction of the figure that is under discussion. Obviously, not *every* Si flake in the microstructure has a β-(Al,Si,Fe) particle attached to its edge, but rather many of them do (Figure 7(a)). Our statement was intended to emphasize the very important role that β-(Al,Si,Fe) particles play in initiating the nucleation of eutectic Si. In hindsight, we submit that the language of the statement could be mistaken by some (as was the case by Dahle and Hillert). Semantics aside, Figure 1 provides ample proof that Si colonies initiate from β-(Al,Si,Fe) particles.

Regarding the second point, we submit that finding the small β-(Al,Si,Fe) particles in an aluminum alloy is a difficult task; however, when enough Fe is used in the experimental samples and with the aid of a focused ion beam (FIB), as we have done, it is possible to find the β-(Al,Si,Fe) particles. Again, Figure 1, together with Figure 2 and Table I, which are reproduced from Reference 3, is ample proof that this is possible. Besides, we are not the first to see β-(Al,Si,Fe) particles in Al-Si alloys (for example, References 4 and 5).

As to the third point, we beg to differ with the presumptuous statement made by Dahle and Hillert; namely, "We are happy to note that they now accept that β particles do not play a major role in the nucleation of the large number of Si plates that are found in a eutectic colony," and we stand by our initial submission that β-(Al,Fe,Si) plays an important role in nucleation of the eutectic phases (particularly eutectic Si) in Al-Si hypoeutectic alloys, and that β-(Al,Fe,Si) *initiates* the nucleation event of eutectic Si.

Finally, Dahle and Hillert proceed to submit, "We believe that the Al-Si eutectic in these alloys initiates on other potent nuclei for silicon present in the alloys, such as AlP." In response to this statement, we offer Figure 3, which we believe is self-explanatory. Moreover, we submit that there is evidence in the open literature that AlP particles participate in the nucleation of primary silicon in hypereutectic alloys. We also submit that AlP particles *may* nucleate eutectic silicon in hypoeutectic alloys; however, we have not seen evidence to support this latter statement. Our study[3] was performed on pure alloys that have a very low P content ($\approx$0.0008).

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