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AN ALTERNATIVE EUTECTIC SYSTEM FOR CASTING ALUMINUM ALLOYS II. MODIFICATION OF THE EUTECTIC MORPHOLOGY

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Abstract

Based on their casting ability and tensile properties, the Al-Ni, Al-Fe, and Al-Fe-Ni eutectic systems have been shown to be potential alternatives to the Al-Si eutectic system for fabricating aluminum casting alloys. The microstructure of these eutectics consists of long fibers within an essentially pure aluminum matrix and it has been envisioned by many that modifying the microstructure by breaking down these fibers would lead to enhanced tensile properties. In this, the second of two papers, a method for effective modification of the microstructure of these eutectics is described and the resulting microstructures and tensile properties of the modified alloys are characterized. It is found that the ultimate tensile strength and yield strength of the modified alloys are lower than those of the unmodified alloys, but their ductility is higher.

Introduction

"*Chemical modification*" refers to the morphological transformation that occurs in the eutectic phases of Al-Si alloys upon addition of trace quantities of certain elements, such as Sr or Na, and converts the otherwise plate-like (*flake*) silicon phase shown in Figure 1(a) to the fine fibrous (*coral-like*) structure of Figure 1(b) [1].

This morphological transformation significantly enhances the mechanical properties and overall performance of components that are cast from these alloys [2]. Consequently, much fundamental research has focused on the Al-Si alloy system since Pacz introduced it into the United States in 1921 [3] and a significant portion of it has been directed towards understanding the mechanism behind the modification of the morphology of the eutectic silicon phase by trace element additions. Over the past 50 years, many mechanisms of eutectic modification have been presented, some of them focusing on the role of eutectic growth [4], and others on the role of eutectic nucleation [5]. A comprehensive overview of these mechanisms is given in Ref. [1].

Recently, Koutsoukis and Makhlouf [5] proposed the binary Al-Ni and Al-Fe eutectics, as well as the ternary Al-Fe-Ni eutectic as alternatives to the Al-Si eutectic for constituting aluminum casting alloys and they showed that these alternative eutectics can impart to Al-based castings tensile properties and castability that are comparable to those contributed by the Al-Si eutectic. Figure 2 shows the morphology of the phases in these alternative eutectics and Table I shows their most important characteristics. Note that the second phase in all three alternative eutectics; i.e., the Al_3Fe (θ-phase), the Al_3Ni (β-phase) and the Al_9FeNi (τ_1-phase) are rod-like [7].

In this, the second of two papers on the topic of alternative eutectics, the possibility of modifying the morphology of the second phase in each of these eutectic systems from rod-like to sphere-like is explored.

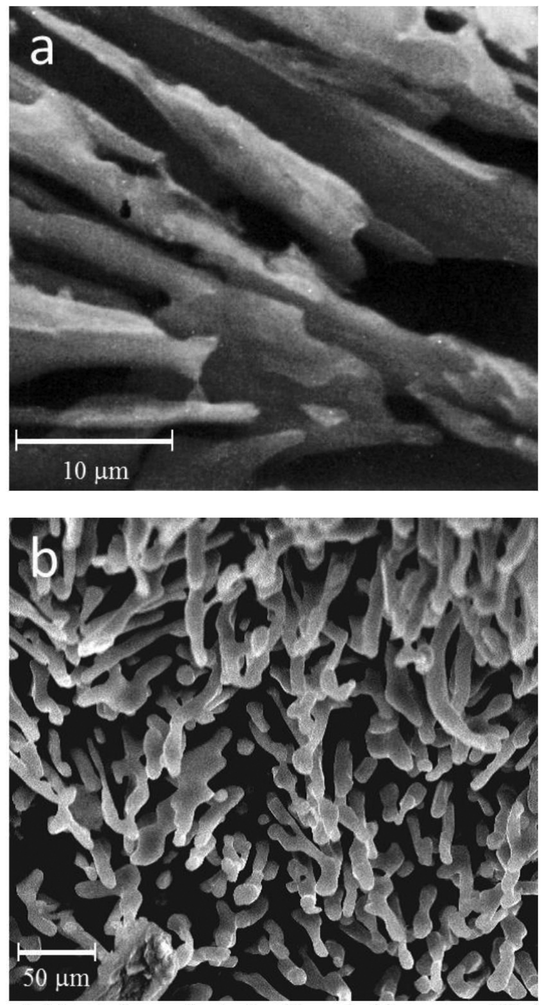

Figure 1. Morphology of eutectic silicon in (a) an unmodified alloy [2] and (b) a Sr-modified alloy.

Two mechanisms are envisioned to cause such modification. The first mechanism builds on the facts that (a) the matrix-fiber interface is characterized by low surface energy, and (b) the fibers do not have circular cross sections, but their cross sections are faceted ellipses [8]. Hence, modification of the fiber morphology should be possible by changing the matrix-fiber interface energy. This could possibly be achieved by making minor chemical additions to the molten metal. The second mechanism is based on the Rayleigh-Plateau Instability Theory [9], which suggests that a cylindrical column of liquid will break down to a row of spherical droplets along its length. The reason for the breakdown is that the column is unstable with respect to geometrical perturbations along its radius [10]. This suggests that heat may exaggerate the geometrical perturbations that may be present along the length of the eutectic fiber causing necking and eventually breakdown of the fiber into small particles.

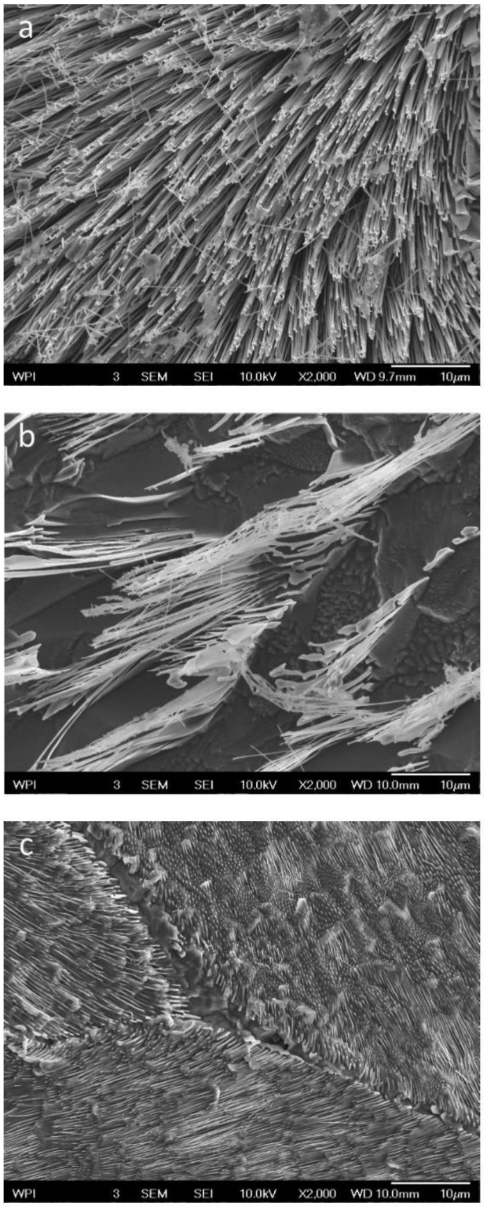

Figure 2. SEM photomicrographs showing the morphology of (a) the Al-Ni, (b) the Al-Fe and (c) the Al-Fe-Ni eutectic.

Table I. Characteristics of the eutectic systems.

Feature	Al-12.6Si	Al-1.8Fe	Al-6.1Ni	Al-1.75Fe-1.25Ni
Eutectic temp. (°C)	577	650	640	~ 650
Eutectic phase (vol. %)	14.4	4.5	9.9	10.2
Phases in the matrix	Si	Al_3Fe (θ)	Al_3Ni (β)	Al_9FeNi (τ_1), (+θ +β)
	diamond cubic	monoclinic	orthorhombic	monoclinic

Materials and Procedure

The eutectic and alloy compositions were constituted from pure aluminum ingots (99.99% purity), Al-15wt% Fe, Al-20wt% Ni and Al-10wt% La master alloys and were melted in an induction furnace in clean silicon carbide crucibles coated with boron nitride. Pouring was performed in a copper mold (1.875 in OD, 2.5 in height) at approximately 800°C. The elemental composition of the molten alloys was measured with spark emission spectroscopy taking 6 to 10 measurements for each alloy. The results were averaged and they are shown in Table II. The melts prepared for casting tensile test specimens were degassed with high purity argon gas by means of a rotating impeller degasser for 30 minutes, and they were also poured at approximately 800°C. Standard round tensile test specimens as described in ASTM standard B557-10 [11] were cast in a cast iron tensile bar mold [12] that was preheated to 427°C.

Table II. Chemical composition of the eutectic systems (wt%).

Alloy	Si	Ni	Fe	Cu	Mn	La	Al
Al-Ni	0.01	6.10	0.02	0.02		0.20-1.00	Bal
Al-Fe	<0.03		1.80	<0.01	0.02		Bal
Al-Ni-Fe	<0.02	1.25	1.75	<0.01	0.01		Bal

Samples were sectioned and prepared for microstructure analysis, they were cut normal to the mold axis close to the center of the mold. The samples were deep-etched with the Poulton's solution and their microstructure was analyzed by means of a field emission scanning electron microscope (SEM) (Jeol, model JSM 7000F). Secondary Electron (SE) images were obtained at 10kV accelerating voltage.

Tensile properties of the samples were measured including ultimate tensile strength (UTS), yield strength (YS), modulus of elasticity (E) and elongation (ε%) [13]. A Universal Testing machine (Instron, model 5500R) was employed at room temperature at an extension rate of 0.1 in/min. A 2-inch gage length extensometer (MTS model 634.25E-24) was used to measure extension. At least 15 specimens were used for each measurement and the results were averaged and the standard deviations were calculated. Fracture of all specimens took place within the gage length and specimens with severe porosity and/or oxides that would affect the results were excluded.

Isothermal heat treatment (HT) of samples was performed at 600°C for 8h, and was followed by air cooling to room temperature. All the numerical results were statistically analyzed and compared using one way ANOVA at a significance level of 5% (α=0.05).

Results and Discussion

A. Modification

Modification of the microstructure was performed by adding relatively small quantities of various Rare Earth (RE) elements to the melts. RE elements are known to affect interfacial energy [2, 14-17]. After considerable experimentation with different RE elements, it was found that La is the most effective. Figure 3 shows the effect of adding 0.5 wt% La on the morphology (i.e., size and shape) of the Al_3Ni fibers of the Al-Ni eutectic.

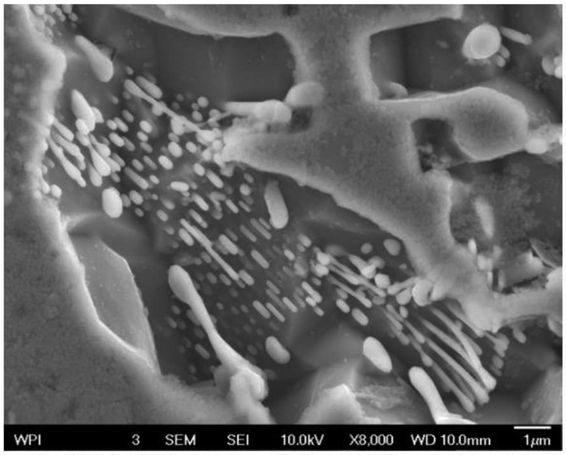

Figure 3. SEM (SE) image of the Al-Ni eutectic chemically modified by adding 0.5 wt% La to the melt.

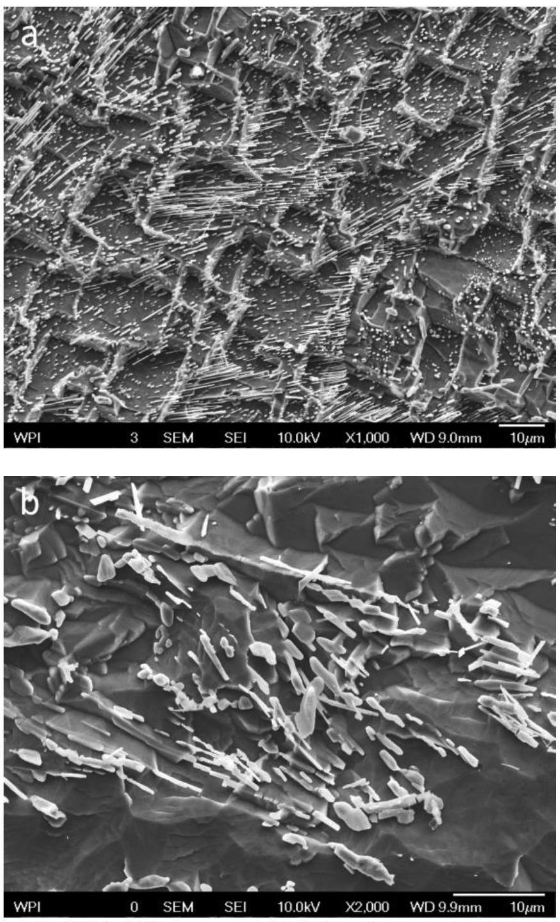

Figure 4. SEM (SE) images of (a) the Al-Fe eutectic heated at 600°C for 8hours and (b) the Al-Fe-Ni ternary eutectic heated at 600°C for 8hours.

Isothermal heating (600°C for 8h) was also used to breakdown the fibers, Figure 4 shows the effect of this isothermal heat treatment on the morphology of the Al_9FeNi fibers of the Al-Fe-Ni ternary eutectic (Figure 4a) and the Al_3Fe fibers of the Al-Fe eutectic (Figure 4b). It is clear from Figures 3 and 4 that the long aluminide fibers that characterize the proposed alternative eutectic systems have been broken down to smaller ones, resulting in what may be characterized as partial modification of the microstructure. In some samples, both La and heat were employed. As Figure 5 shows, with this combined treatment, the microstructure of the Al-Ni eutectic (Figure 5a) and that of the Al-Fe-Ni eutectic (Figure 5b) were completely modified by adding 0.2 wt% La to the melt and heating the castings to 600°C for 8hours.

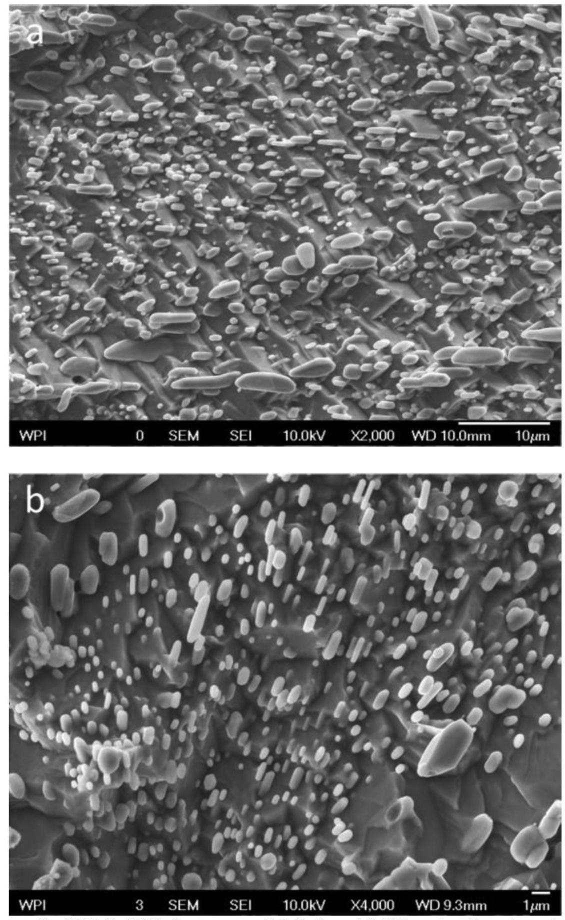

Figure 5. SEM (SE) images of (a) the Al-Ni eutectic chemically modified by adding 0.2 wt% La to the melt and heating the castings at 600°C for 8 hours and (b) the Al-Fe-Ni ternary eutectic chemically modified by adding 0.2 wt% La to the melt and heating the castings at 600°C for 8 hours.

B. Tensile Properties

Table III shows the measured room temperature tensile properties for the Al-Ni eutectic in the unmodified condition, the La-modified condition, and the (La+HT)-modified condition. For ease of visualization, the same information is presented graphically in Figure 6.

Table III. Measured room temperature tensile properties of the Al-Ni eutectic.

	UTS (MPa)	YS MPa)	E (GPa)	ε (%)
Unmodified	188±7	113±9	68±5	7.0±1.6
+ 0.5La	161±5	79±3	61±5	7.5±0.6
+ 0.5La, 600°C-8h	128±1	58±2	64±5	20.0±1.7

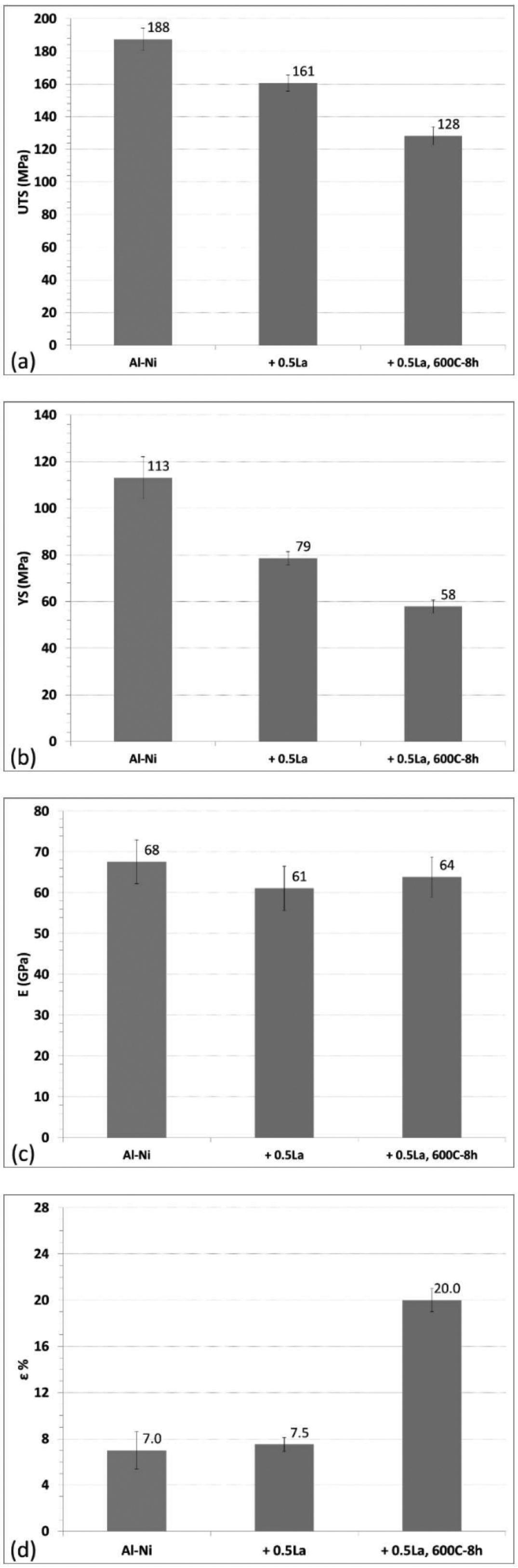

Figure 6. Measured room temperature tensile properties of the Al-Ni eutectic: (a) ultimate tensile strength, (b) yield strength, (c) modulus of elasticity, and (d) elongation.

Similarly, Figure 7 and Table IV show the measured room temperature tensile properties for the ternary Al-Fe-Ni eutectic in the unmodified condition, the La-modified condition, and the (La+HT)-modified condition.

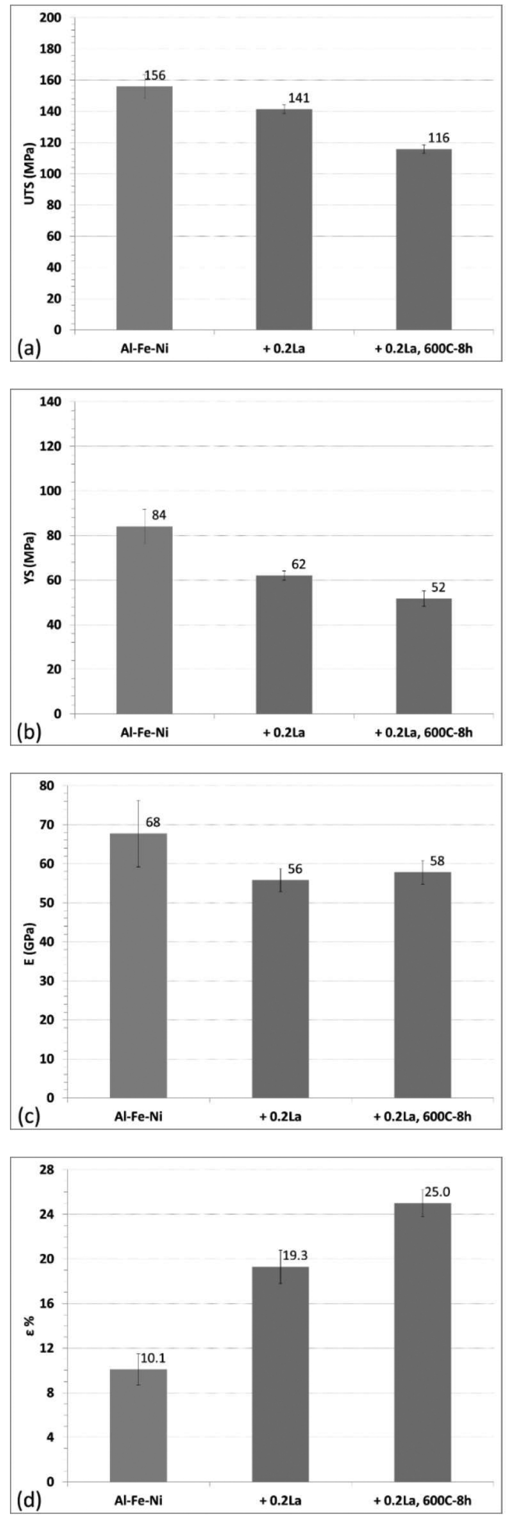

Figure 7. Measured room temperature tensile properties of the Al-Ni eutectic: (a) ultimate tensile strength, (b) yield strength, (c) modulus of elasticity, and (d) elongation.

It is clear from Figures 6 and 7 that the UTS and YS of the Al-Ni eutectic are higher than the UTS and YS of the ternary Al-Fe-Ni eutectic. This is attributed to the presence of the Al_3Ni phase [11]. This phase is coherent with the α-aluminum matrix, which accounts for its thermal stability [14,15,17].

Table IV. Measured room temperature tensile properties of the Al-Fe-Ni eutectic.

	UTS (MPa)	YS (MPa)	E (GPa)	ε (%)
Al-Fe-Ni	156±8	84±8	68±8	10.1±1.4
+ 0.2La	141±3	62±2	56±3	19.3±1.5
+ 0.2La, 600°C-8h	116±2	52±3	58±6	25.0±1.7

It is also clear from Figures 6 and 7 that modification performed as described in this paper has a negative effect on the UTS and YS of both the Al-Ni and Al-Fe-Ni eutectics with the drop in UTS and YS upon modification of the Al-Ni eutectic being larger than the drop in the UTS and YS of the Al-Fe-Ni eutectic. Elongation, on the other hand, is significantly improved by this modification method. The loss of strength upon modification may seem counter intuitive since the finer and more uniform microstructure that is characteristic of the modified morphology is expected to enhance strength. However, it seems that breaking down the long aluminide fibers made it easier for dislocations to move within the α-aluminum matrix which is reflected in the increased elongation.

Conclusions

- Modification of the Al-Ni and the Al-Fe-Ni eutectic systems can be effected by small Lanthanum additions to the melt and heating the castings at 600°C for 8 hours. Only limited modification occurs in the Al-Fe eutectic under these conditions.
- About 0.5 wt% Lanthanum followed by isothermal heating at 600°C for 8 hours causes full modification of the microstructure of the Al-Ni eutectic.
- About 0.2 wt% Lanthanum followed by isothermal heating at 600°C for 8 hours causes full modification of the microstructure of the ternary Al-Fe-Ni eutectic.
- Chemical modification with Lanthanum combined with heating the castings at 600°C for 8 hours significantly increases elongation and decreases the ultimate tensile strength and the yield strength of the Al-Ni and Al-Fe-Ni eutectics.

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