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Study on the properties of Al–23%Si alloy treated by ultrasonic wave

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ABSTRACT

Al–23%Si alloy was treated using a novel ultrasonic system. The properties of the alloy were investigated. The results show that the microhardness of the alloy treated by ultrasonic wave was distributed more uniformly than that untreated by ultrasonic wave. The ultimate tensile strength of the alloy treated by ultrasonic wave was higher than that of the alloy untreated by ultrasonic wave. The alloy treated by ultrasonic wave had a more obvious strain hardening behavior. But there were more dimples of ductile failure on the fracture surface of the alloy untreated by ultrasonic wave. The change of the friction coefficient of the alloy treated by ultrasonic wave with increasing sliding time was small. The wear resistance of the alloy treated by ultrasonic wave was better than that untreated by ultrasonic wave.

1. Introduction

Hypereutectic Al–Si cast alloys are especially suitable for tribological parts owing to their excellent wear resistance provided by the primary Si particles [1–5]. However, their machinability and ductility are poor. The mechanical properties of Al–Si alloys depend mainly on the size, shape and distribution of Si in the alloys. It is effective to change the morphology and size of Si in order to decrease the weakening effect of Si on the matrix and improve the properties of Al–Si alloys [2–6]. The Al–Si alloys will have excellent mechanical properties as long as the Si phases, either the eutectic Si or primary Si, are fine and distribute uniformly in matrix [2–4].

The control of the microstructures of castings is considered as one of the main challenge in foundry industry, by which the optimal mechanical properties can be obtained with the lowest cost and shortest process time [7]. In recent years, the mechanical modification, including electromagnetic stirring or mechanical vibration to induce forced convection in the melt, has been developed and applied successfully in foundry industry [8]. With the rapid development of the power ultrasonic technology, ultrasonic treatment as a new technology is being used widely for improving the solidification structure of Al–Si alloys. The injection of ultrasonic energy into molten alloys can bring about some nonlinear effects, such as cavitation and acoustic stream, which can be used to refine microstructures, reduce segregation and degas [9,10].

The goal of this work is to investigate the influence of ultrasonic treatment on the properties of Al–23%Si alloy and to develop a simple and economical method to modify the hypereutectic Al–Si alloys.

2. Experimental

2.1. Material

Commercial Al–23%Si alloy was used as the raw material. Its chemical composition was listed in Table 1.

2.2. Ultrasonic treatment of Al–23%Si alloy melt

The ultrasonic treatment equipment consists of the temperature and power control systems [11]. The treating temperature was monitored with a temperature sensor. In this work, a horn crucible was designed and fabricated [11]. Prior to the ultrasonic treatment, the horn crucible was vertically bolted with a 20 kHz transducer. When the ultrasonic treatment of the alloy melt was carried out, the ultrasonic wave emitted from the transducer and passed through the horn crucible was propagated direct into the melt. So the acoustic energy acted on the melt was raised remarkably.

Al–23%Si alloy of 200 g was melted using an intelligently numerical controlled electric resistance furnace. The melt was heated to 800 °C, and then it was poured to the horn crucible preheated to 680 °C and treated with ultrasonic wave for 10 min. The ultrasonic power was 150 W and the amplitude was 4 μm. After that, the horn crucible was moved out the ultrasonic system and was immediately quenched with the water of 25 °C.

2.3. Studies on the microstructures and properties of Al–23%Si alloy

The microstructures of the samples were investigated using Olympus GX51 optical microscope and JSM-5600 scanning electron microscopy (SEM).

The microhardness of samples was measured using 430/450 SVD Vickers hardness tester. The load is 30 g, and the holding time is 10 s. Reported hardness is the average of three data.

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Table 1
Chemical composition of Al–23%Si alloy (wt.%).

Si	Mn	Cu	Ti	Fe	Zn	Mg	Al
23	0.01	0.08	0.02	0.5	0.005	0.101	Balance

The tensile tests of samples were carried out at ambient temperature of 300 K using a WSM-50KB tensile machine. The crosshead speed was 1 mm/min. The stress and strain curves were provided as a computer output by the control unit of the test machine. The fracture surface was analyzed using SEM.

The dry sliding tests were conducted at room temperature with an M-200 model block-on-ring friction and wear tester. The block specimen was loaded against a steel ring by a dead weight loading system. The size of the block specimen is 10 mm × 10 mm × 14 mm. The steel ring (Ø 40 mm × 10 mm) as a counterpart was made of hardened and tempered steel (HRC65 ± 5). The sliding velocity was 0.42 m/s, the applied load was 30 and 50 N, and the sliding time was 20 and 40 min, respectively. Prior to the tests, the surfaces of the block specimens and steel ring were abraded with No. 1000 water-abrasive paper and cleaned with acetone-dipped cotton. An electronic weighing balance of 0.01 mg accuracy was used to weigh the block specimens before and after tests to obtain the wear mass loss. The friction coefficient μ was calculated with the following equation [12]:

$$\mu = \frac{T}{RP} \quad (1)$$

where T is the friction torque, R the radius of the steel ring, and P the applied load. Three repeated tests were carried out for each specimen in order to minimize the data scattering. The worn surfaces were analyzed using SEM to reveal the wear mechanisms of the specimens.

3. Results and discussion

3.1. Microhardness of Al–23%Si alloy

The microhardness of different phases in hypereutectic Al–Si alloys is different. Among the microhardness of the hypereutectic Al–Si alloy microstructures (primary Si phase, eutectic structure and α-Al phase), the microhardness of primary Si is the highest, and the microhardness of α-Al phase is the lowest. Therefore, the microhardness in different positions of hypereutectic Al–Si alloy samples with and without ultrasonic treatment is different. The homogeneity of the microhardness on the surface of hypereutectic Al–Si alloy sample can qualitatively reflect the homogeneity of the structure distribution of hypereutectic Al–Si alloy samples with and without ultrasonic treatment.

Fig. 1 shows the statistical results of the microhardness of Al–23%Si alloy samples without and with ultrasonic treatment. It can be found that the numbers of low hardness values and high hardness values in the alloy without ultrasonic treatment are all more than those with ultrasonic treatment, and the hardness range of the alloy with ultrasonic treatment is mainly between 80 and 105 HV. That is to say, the distribution of the microhardness of the alloy with ultrasonic treatment is more centralized and uniform than that without ultrasonic treatment. This distribution rule of the microhardness of the alloy samples with and without ultrasonic treatment was determined by the distribution of different microstructures of Al–23%Si alloy samples without and with ultrasonic treatment. Fig. 2 shows the microstructures of Al–23%Si alloy samples without and with ultrasonic treatment. It can be found that when the alloy was not treated with ultrasonic wave (Fig. 2(a)), the contents of the structures with low microhardness (α-Al phase and gas holes) and high microhardness (primary Si phase) were more. When the alloy was treated with ultrasonic wave (Fig. 2(b)), there were more eutectic structure, the primary Si phase was fine and distributed uniformly, and the content of α-Al phase and gas holes decreased. This means that the structure distribution of the alloy with ultrasonic treatment is more uniform than that without ultrasonic treatment, so the microhardness distribution of the alloy with ultrasonic treatment is more uniform than that without ultrasonic treatment.

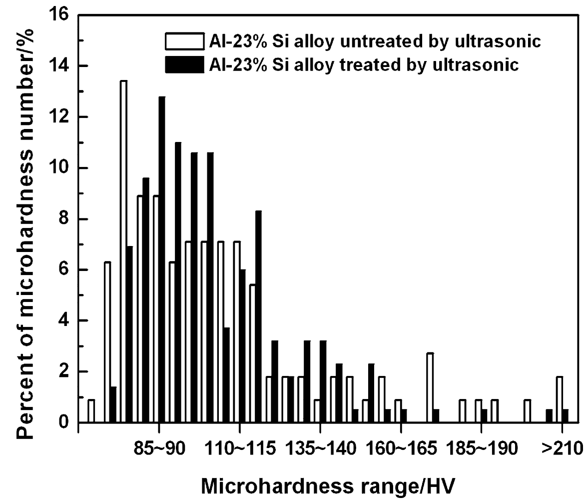

Fig. 1. Statistical results of the microhardness of Al–23%Si alloy.

3.2. Tensile properties of Al–23%Si alloy

Fig. 3 shows the tensile stress–strain curves of Al–23%Si alloy samples without and with ultrasonic treatment. The result shows that the ultimate tensile strength of the alloy treated by ultrasonic wave was higher than that untreated by ultrasonic wave. This phenomenon can be explained by the change of the microstructures of the alloy samples without and with ultrasonic treatment. Compared with the microstructures of the alloy without ultrasonic treatment, on the one hand, the primary Si was refined and all phases distributed uniformly in the alloy with ultrasonic treatment (Fig. 2(b)); on the other hand, the gas pores decreased or disappeared (Fig. 2(b)) and the microstructures became compact after the Al–23%Si alloy

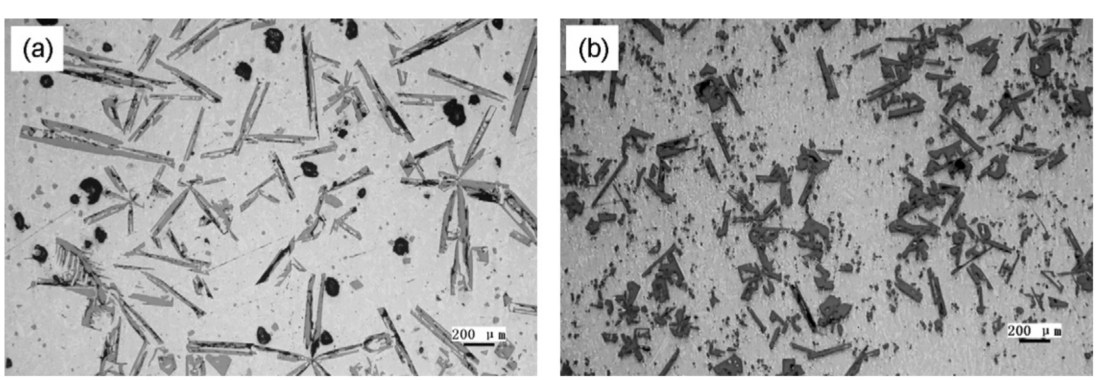

Fig. 2. Microstructures of Al–23%Si alloy samples untreated by ultrasonic wave (a) treated by ultrasonic wave (b).

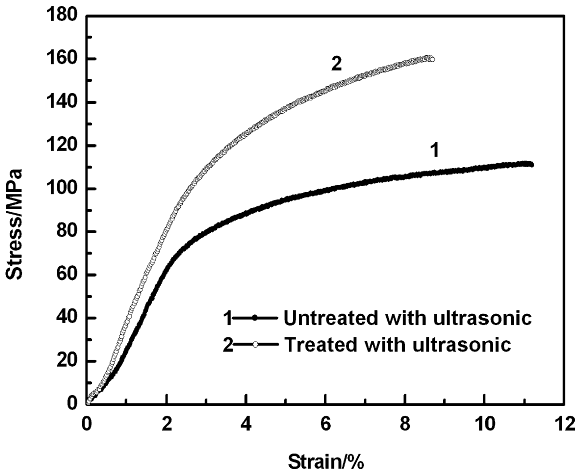

Fig. 3. Stress–strain curves of Al–23%Si alloy samples untreated and treated by ultrasonic wave.

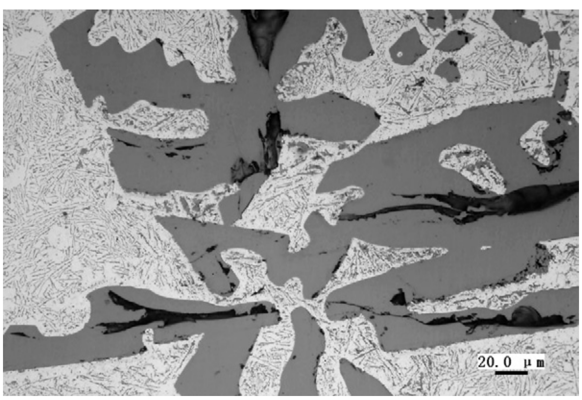

Fig. 4. Primary Si in Al–23%Si alloy treated by ultrasonic wave.

was treated by ultrasonic wave. In addition, the edges of the primary Si phase became circinal and smooth (Fig. 4), which resulted in the decrease of the stress concentration during bearing the load. These are the main reasons why the alloy treated by ultrasonic wave was of higher ultimate tensile strength.

It can be also found from Fig. 3 that the alloy untreated by ultrasonic wave had a strain hardening phenomenon, and the ultimate tensile strength of 111 MPa was reached at the strain of 11.2%. Whereas the strain hardening behavior of the alloy treated by ultrasonic wave was more obvious, and the ultimate tensile strength of 160 MPa was obtained at the strain of 8.7%. This indicated that the strength of the alloy treated by ultrasonic wave increased and its elongation reduced. Fig. 5 shows the tensile fracture surfaces of Al–23%Si alloy samples untreated and treated by ultrasonic wave. It can be found that there were more dimples of ductile failure on the fracture surface of the alloy untreated by ultrasonic wave (Fig. 5(a)) than those treated by ultrasonic wave (Fig. 5(b)). This indicates that the ductility of the alloy with ultrasonic treatment decreased. This result accorded with the tensile stress–strain curves of the alloys (Fig. 3).

3.3. Friction and wear properties of Al–23%Si alloy

3.3.1. Friction coefficient

The variation of the friction coefficients of Al–23%Si alloy samples without and with ultrasonic treatment with the siding time at the applied loads of 30 and 50 N was shown in Fig. 6(a). It can be seen that the friction coefficient of the sample untreated by ultrasonic wave increased initially with increasing sliding time and then kept steady after about 12 min, and the change of the friction coefficient of the sample treated by ultrasonic wave with increasing sliding time was small. The friction coefficient at the applied load of 30 N was lower than that at the applied load of 50 N. However, the friction coefficient of the alloy without ultrasonic treatment in steady stage was close to that with ultrasonic treatment.

At the initial stage of the sliding, the coarse primary Si particles in the sample untreated with ultrasonic wave were easy to break up and desquamate, which resulted in the increase of the roughness of the sliding surface and the fluctuations of the friction force and friction coefficient. With the increase in the sliding time, the small pits on the sliding surface were filled gradually with soft α-Al phase, so the friction coefficient became steady at the steady stage. Whereas the primary Si particles in the sample treated with ultrasonic wave were fine and distributed uniformly, and the roughness of the sliding surface changed hardly at whole sliding process, so the fluctuation scope of the friction coefficient was not big.

3.3.2. Wear resistance

Fig. 6(b) shows the wear mass losses of the alloy samples without and with ultrasonic treatment at different applied loads and sliding time. It can be found that the wear resistance of the alloy with ultrasonic treatment was better than that without ultrasonic treatment under the same testing condition. The reason was that the primary Si particles in the alloy treated with ultrasonic wave were much small and were uniformly distributed, and they increased the resistance to the thermal softening and plastic deformation. In addition, compared with the alloy untreated with ultrasonic wave, the small primary Si particles were not easy to break up and desquamate.

3.3.3. Morphologies of the worn surfaces

Fig. 7 shows the morphologies of the worn surfaces of Al–23%Si alloy samples without and with ultrasonic treatment. It can be

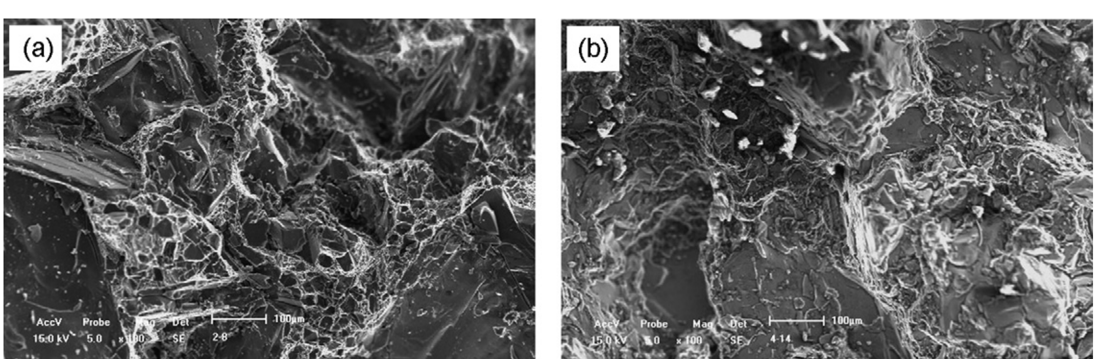

Fig. 5. Fracture surface of Al–23%Si alloy samples (a) untreated by ultrasonic wave (b) treated by ultrasonic wave.

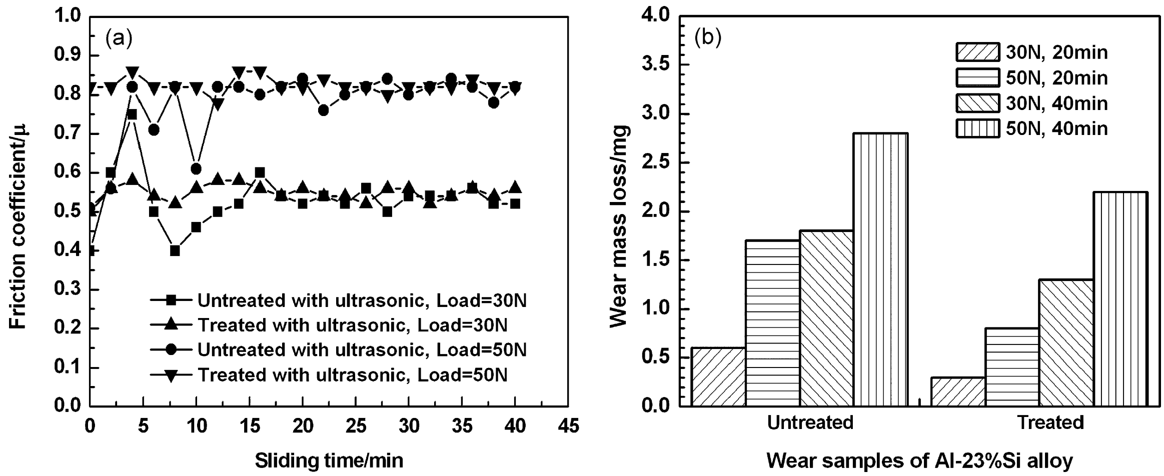

Fig. 6. Friction coefficient and wear mass loss of Al–23%Si alloy samples without and with ultrasonic treatment.

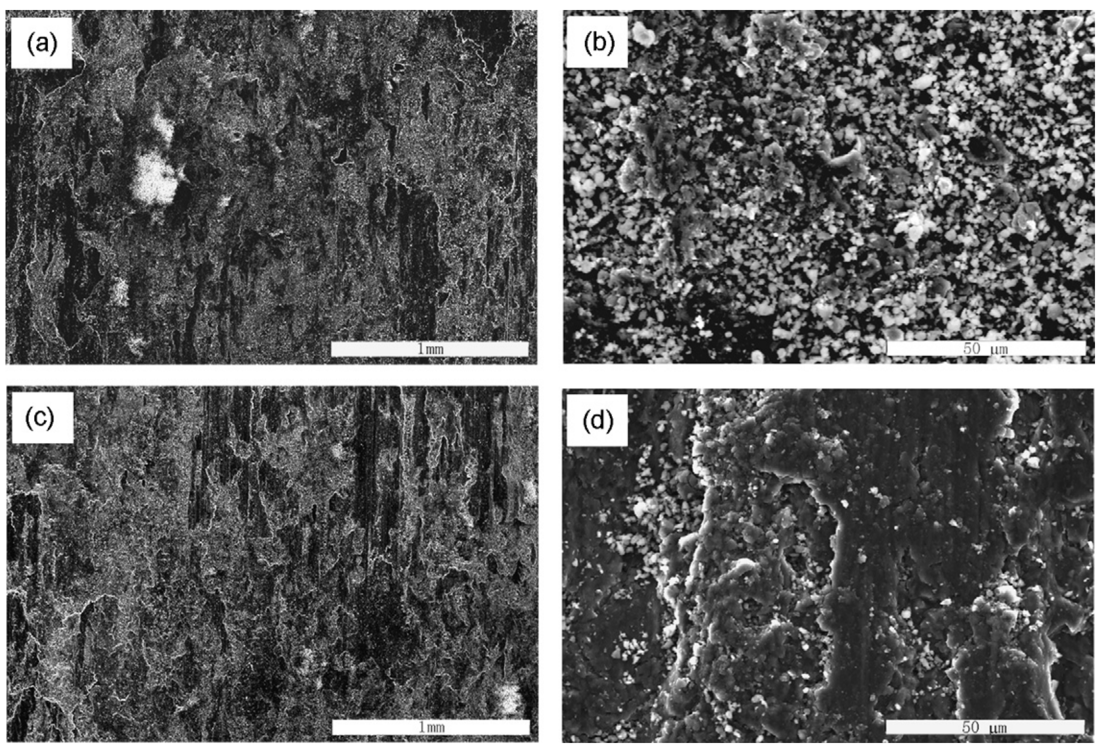

Fig. 7. Morphologies of worn surfaces of Al–23%Si alloy samples at the load of 50 N and sliding time of 40 min ((a) (b) without ultrasonic treatment, (c) (d) with ultrasonic treatment).

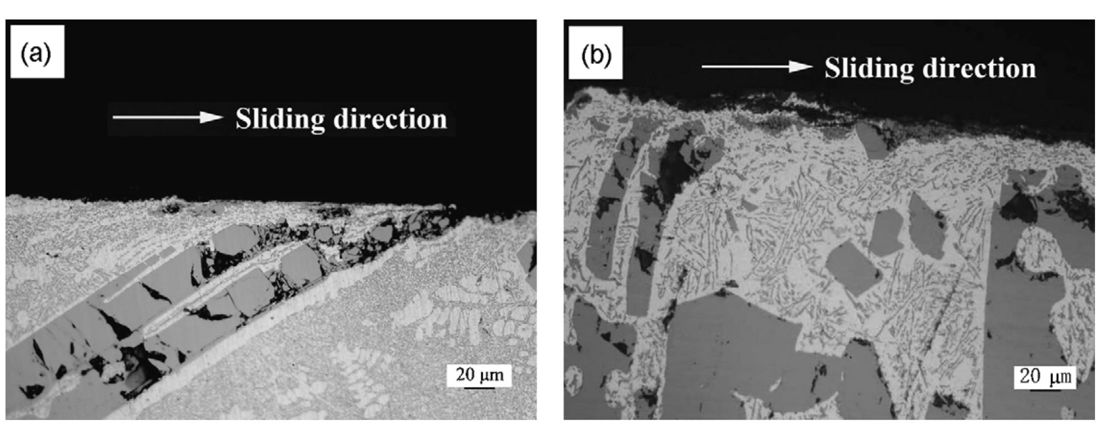

Fig. 8. Cross section structure of worn Al–23%Si alloy samples untreated by ultrasonic wave (a) and treated by ultrasonic wave (b) at the load of 50 N and sliding time of 40 min.

seen that the worn surface of Al–23%Si alloy untreated by ultrasonic wave was not smooth (Fig. 7(a)), was covered by some small debris (Fig. 7(b)), and had few ploughing grooves. The worn surface of Al–23%Si alloy treated by ultrasonic wave was smoother than that untreated by ultrasonic wave (Fig. 7(c)) and had many ploughing grooves (Fig. 7(d)). To reveal the effect of primary Si on the wear behavior further, the microstructures of the worn subsurface were observed (Fig. 8). It can be seen that there existed a fluid deformation zone along the sliding direction at the worn subsurface. The primary Si was broken to pieces seriously in the subsurface of the alloy untreated with ultrasonic wave (Fig. 8(a)). On the contrary the depth of the plastic deformation was small in the subsurface of the alloy treated with ultrasonic wave, and the fluid deformation in the subsurface was unconspicuous (Fig. 8(b)).

4. Conclusions

1. The microhardness of Al–23%Si alloy treated by ultrasonic wave was distributed more uniformly than that untreated by ultrasonic wave.
2. The ultimate tensile strength of Al–23%Si alloy treated by ultrasonic wave was higher than that untreated by ultrasonic wave. The Al–23%Si alloy treated by ultrasonic wave had a more obvious strain hardening behavior. But there were more dimples of ductile failure on the fracture surface of Al–23%Si alloy untreated by ultrasonic wave.
3. The change of the friction coefficient of Al–23%Si alloy treated by ultrasonic wave with increasing sliding time was small. The wear resistance of Al–23%Si alloy with ultrasonic treatment was better than that without ultrasonic treatment under the same condition.

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