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Influence of Aging Conditions on Fatigue Fracture Behaviour of 6063 Aluminum Alloy

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تأثير الظروف الزمنية على سلوك كسر إجهاد سبيكة الألومنيوم 6063

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خلاصة : تمت في هذه الدراسة المعالجة الحرارية لسبيكة من الألمونيوم والمغنيسيوم والسيليكون (6063(Al-Mg-Si بإستخدام درجات حرارة أقل و أعلى من أفضل درجة حرارة للمعاملة الحرارية للسبيكة. وقد تم إختيار عدد الدورات الضرورية لإحداث كسور إجهاد تحت جهد ثابت كمعيار على مقاومة الإجهاد. وتم تقييم سطح الكسر للسبيكة تحت ظروف زمنية مختلفة بواسطة الميكروسكوب البصري والميكروسكوب الإلكتروني الكاشف. كما وأكدت الصور الإلكترونية وجود سطوح شقوق مع خطوط محددة للإجهاد. ولوحظ بأن زمن ودرجة حرارة السبيكة تنتج أشكال كسور مختلفة. ووجد بأن أفضل زمن ودرجة حرارة للتقسية يقع ما بين 4 إلى 5 ساعات مع درجة حرارة 460 كيلفن. هذا ويمكن أن تعزى الزيادة في خاصية الكسور الإجهادية للسبيكة نتيجة زيادة مدة التقسية إلى وجود ظاهرة الإنتشار المدعم بالفراغات للحبيبات الصغيرة الناتجة عن المعاملة الحرارية، أو إلى تثبيت حركات الإزاحة بواسطة الترسيب الناتج خلال مدة المعاملة. وعلى أية حال، فإن قلة مقاومة الإجهاد للمدد الزائدة للسبائك يمكن أن تعزى إلى تشكل حبيبات كبيرة من الحبيبات الصغيرة.

ABSTRACT: Aluminum - Magnesium - Silicon (Al-Mg-Si) 6063 alloy was heat-treated using under aged, peak aged and overage temperatures. The numbers of cycles required to cause the fatigue fracture, at constant stress, was considered as criteria for the fatigue resistance. Moreover, the fractured surface of the alloy at different aging conditions was evaluated by optical microscopy and the Scanning Electron Microscopy (SEM). The SEM micrographs confirmed the cleavage surfaces with well-defined fatigue striations. It has been observed that the various aging time and temperature of the 6063 Al-alloy, produces different modes of fractures. The most suitable age hardening time and temperature was found to be between 4 to 5 hours and to occur at 460 K. The increase in fatigue fracture property of the alloy due to aging could be attributed to a vacancy assisted diffusion mechanism or due to pinning of dislocations movement by the precipitates produced during aging. However, the decrease in the fatigue resistance, for the over aged alloys, might be due to the coalescence of precipitates into larger grains.

KEYWORDS: Age Hardening, Fatigue, Fracture, Precipitation Hardening.

1. Introduction

Aluminum alloys have gained a lot of importance due to good mechanical and corrosion resistance properties. Aluminum alloys, of type 6063, which consist of aluminum magnesium, and silicon, are used in several industrial applications (Thornton and Colangelo, 1985). The addition of magnesium and silicon improves the castability as well as corrosion resistance of these alloys (Helby, 1993). Alloy 6063 is produced at different tempered conditions, depending on the application required (Hunsicker,1967). The tempered conditions (i.e., the solutionizing temperature, aging temperature and aging time) are responsible for the wide range of the mechanical properties exhibited by this alloy. Okorafor (1991) studied the effect of 3.5% NaCl solution on corrosion resistance properties of under aged, peak aged and over aged specimen by means of weight loss measurement and a potentiokinetic polarization technique. The results obtained showed that the weight loss and the rate of weight loss were functions of both heat treatment and exposure time.

Zajac *et al* (1993) investigated the hot deformation behavior of AA 6063 and AA 6005. It was found that addition of small amounts of manganese significantly helps in homogenizing and transforming the plate like beta AlFeSi phase to more rounded alpha AlFeSi phase, which increases the ductility of the material. Musulin and Celliers (1990) confirmed that the addition of manganese also increases quench sensitivity of the alloy even when the cooling rate is as low as 50 ^{o}C per minute. It was found that the addition of manganese accelerates the transformation of beta AlFeSi phase to a favorable alpha AlFeSi phase.

Fatigue crack propagation in crystalline material is normally divided into two successive stages as investigated by Jiang *et al* (1990a). It was concluded from their experimental work that in stage I a crack develops along the active slip plane and normal to the direction of applied stress. In stage II, the propagation of the crack begins in under aged 6063 Al-Mg-Si alloys. The alloy exhibits heterogeneous deformation and slip bands are formed only by one slip system. There is a strong tendency for single slip system activation, which can be attributed to the high volume fraction and small size of GP zone and low content of dispersoids.

Jiang *et al* (1990 b) studied the effect of different aging conditions on fatigue fracture behavior of Al-Mg-Si alloy with different chemical composition and dispersoid contents. They found that the dispersoid phase could alter the mode of fatigue fracture by influencing the deformation uniformity of the alloy. The 6063 A-A system used for vertical axis wind turbine blades was investigated by Van Den Avyle and Sutherland (1988). Fatigue analysis for typical materials includes two types of data (a) stress versus number of cycles (S-N curve); and (b) fatigue crack growth rate. The S-N experiment was conducted on A-A 6063 extruded material using 100 bend specimens cycled at fine alternating stress amplitudes. The cyclic crack growth rates were measured using three loading rates.

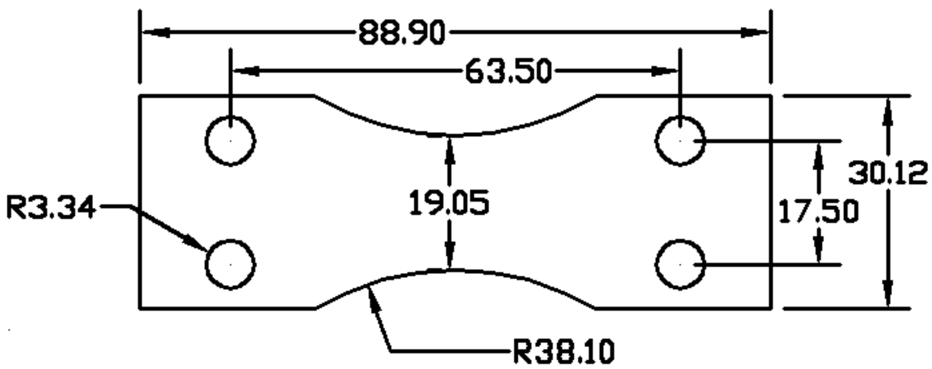

Figure 1. Standard fatigue specimen according to BS3518 specification in mm.

Although considerable work has been conducted on the effect of precipitation, fatigue resistance and age-hardening parameters of 6063 Al-Si-Mg alloy (Jiang *et.al*1990 a, Jiang *et al* 1990 b, VanDen Avyle and Sutherland 1988), there is still a need to investigate the combined effect of time and temperature on the fatigue properties.

2. Experimental Procedure

Extruded bars made from 6063 A-A were produced by Oman National Aluminum Company from continuously cast billets. Chemical composition is given in Table 1.

Fatigue test specimens were prepared from extruded profiles in the College of Engineering workshop at Sultan Qaboos University, according to the BSI 3518 standard specification, as shown in Figure 1. Solution heat treatment of the prepared specimens was conducted by soaking them at 793 K for 2.5 hours in a furnace followed by quenching in cold water to preserve the super saturated solid solution Al-Mg-Si alloy at room temperature. All the specimens were then kept in the deep freeze zone of the refrigerator to prevent natural aging that might occur at room temperature. The age hardening treatments were conducted in a pick stone oven at temperatures 320K, 340K, 360K, 380K, 400 K, 420 K, 440 K, 460 K, 480 K, 500K, 520K, 540K and 560K

Table 1: Chemical composition of 6063 Al-Alloy.

Elements	Al	Si	Mg	Fe	Mn	Cu
Wt%	Balance	0.475	0.537	0.096	0.078	0.085

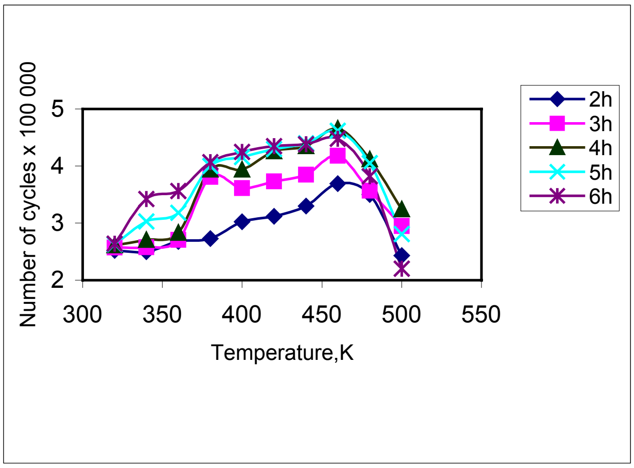

Figure 2. Effect of aging temperature at constant time on fatigue resistance properties of 6063 A-A.

using different intervals i.e. 2h, 3h, 4h, 5h and 6h. The fractured surfaces of the specimens were examined using light and electron microscope. Cyclic fatigue tests were conducted at room temperature, using the Every Denson fatigue-testing machine. Constant applied stress of 339 kPa was used until fracture occurred. The number of cycles required to fracture the specimen was counted and taken as a criterion for the fatigue resistance.

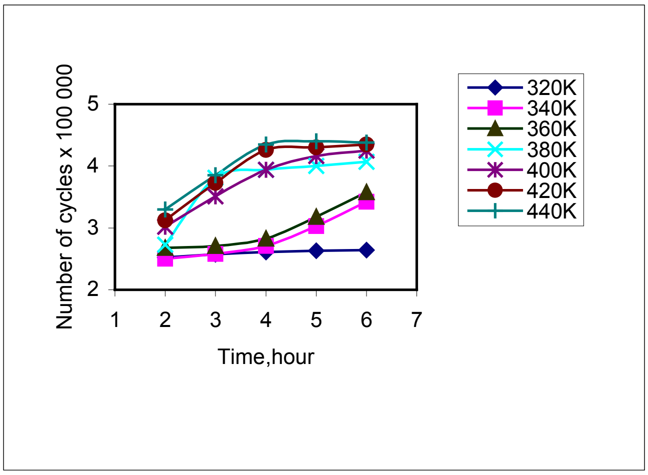

Figure 3. Effect of aging time at constant temperature (320-440 K) on fatigue resistance properties of 6063 A-A.

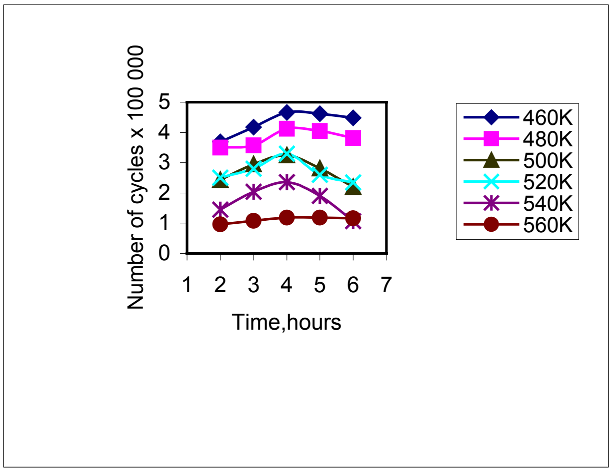

Figure 4. Effect of aging time at constant temperature (460-560 K) on fatigue resistance properties of 6063 A-A.

3. Results and Discussion

The effect of precipitation heat treatment time and temperature on the fatigue fracture behavior of 6063 A-A is shown in Figures 2-4. It is observed that, as the aging temperature increases, an increase in number of cycles to fail at constant stress is noticed (Figure 2). Further increase in temperature causes a sharp increase in number of cycles to fail when heat-treated between 360 K–460 K. Any further increase in precipitation heat treatment temperature would cause a decrease in the number of cycles to fail at constant stress in the 6063-aluminum alloy. From Figure 2 it is confirmed that the best aging temperature is 460 K when the alloy can have maximum fatigue resistance property.

Figures 3 and 4 represent the effect of variable time on the fatigue fracture behavior of 6063 A-A at constant temperature and constant stress. It is clear from the experimental results (Figures 3-4) that the number of cycles required to fail increases with the increase in precipitation hardening time. However, if the heat treatment is carried out for more than 5 hours at higher temperature, the 6063 A-A will fail earlier. It is observed from Figures 2-4 that the best time at which the 6063-aluminum alloy can be made more resistant to cyclic loading at constant stress is between 4 to 5 hours. A further increase in age hardening time will cause an earlier failure in the Al-alloy. It is evident from Figures 2-4 that the best precipitation hardening time and temperature for 6063 aluminum alloy is between 4 to 5 hours at 460 K.

Figures 5 and 6 show the fatigue cracks in a partially and completely broken specimen. The crack path is irregular and gives an indication of a cleavage crack. Most of the partially broken specimens show the same pattern of crack initiation, propagation and termination in peak aged and over aged alloy. The photographic view of the completely broken section of 6063 alloys after fatigue test, is shown in Figure 6. The irregular crack pattern and crack surface indicates less ductility in the material and fracture appears almost like brittle fracture.

An SEM micrograph of 6063 aluminum alloy fractured surface is shown in Figure 7 when aged for 3 h at 370 K. The photomicrograph shows a number of plateaus that are at different elevations with respect to each other. These plateaus are joined together by a wall which contains fatigue striations. At certain places some cracks are also observed along with the striations.

Figure 8 represents a fracture surface of 6063 A-A when heat-treated at 480K for a period of 5 hours. The micrograph shows fatigue striations which are in step like formation. The alloy was heated to peak aged temperature, which has reduced the ductility of the alloy, the surface exhibits a brittle pattern along with widely spaced striations that are nearly parallel to the grain boundary. These striations seemed to be formed by cleavage fracture.

The same specimen when observed at other positions in SEM also shows a cleavage fracture pattern. The fracture was initiated on many parallel cleavage planes (Figure 9). The cleavage surface also shows fine cleavage steps in the photomicrograph. The lower left hand side of the micrograph shows some parts of the material that have failed with inter-granular behavior. Figure 10 represents a view of low cycle fatigue fractured surface. The specimen was aged for 6 h at 560K. The photomicrograph shows well defined fatigue striations that are clearly visible in SEM. It also shows secondary cracks along with striations at a few places within the grains. Few cleavage steps are visible which also confirms that the ductility of the 6063 alloys is reduced due to over aging.

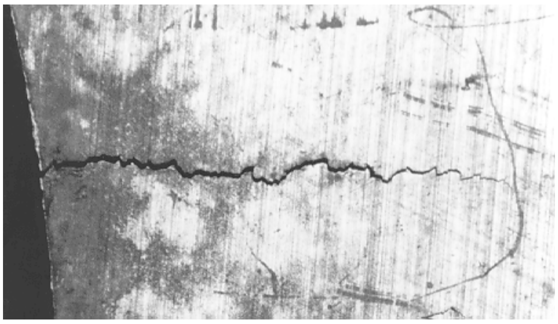

Figure 5. Crack initiation and propagation in 6063 Al-Alloy, aged for 3 h at 350 K.

Figure 6. Fracture surface of 6063 Al-Alloy, aged for 5 h at 460 K.

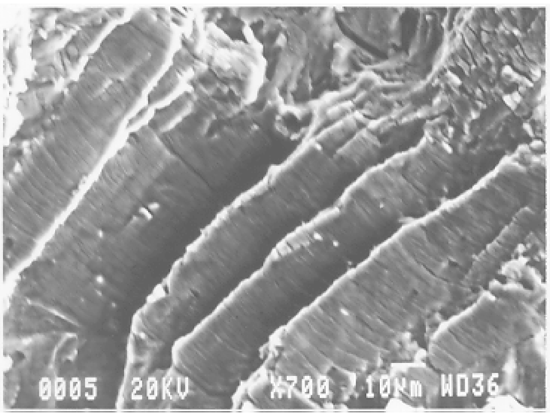

Figure 7. Fatigue striations in 6063 Al-Alloy, aged for 3 h at 370 K.

From the present investigation, it is concluded that the fatigue fracture behavior is very much dependent on the type, size distribution and amount of the precipitated particles produced during precipitation heat treatment (time and temperature). In the under aged (360 K) and peak aged (460-480 K) conditions, the precipitates are heterogeneously dispersed. The heterogeneous dispersion behavior of the precipitates is very complex and it depends on many factors such as boundaries, precipitation behavior, heating time and temperature, etc. (Anderson, 1959).

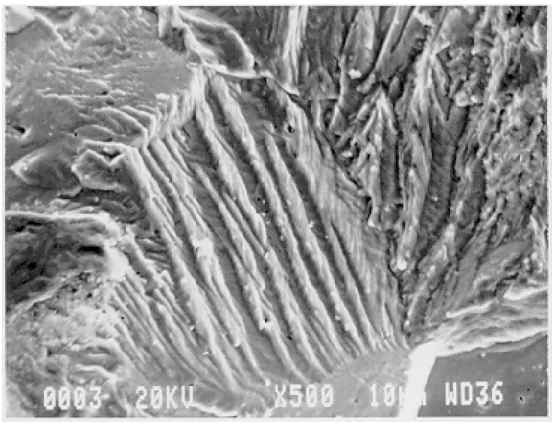

Figure 8. Cleavage fracture with fatigue striations, aged for 5 h at 480 K.

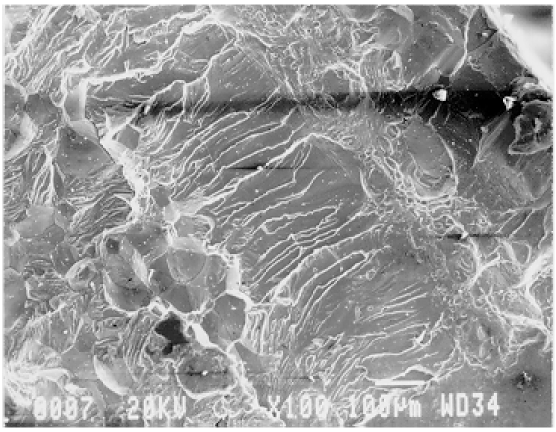

Figure 9. Cleavage fracture, aged for 5 h at 480 K.

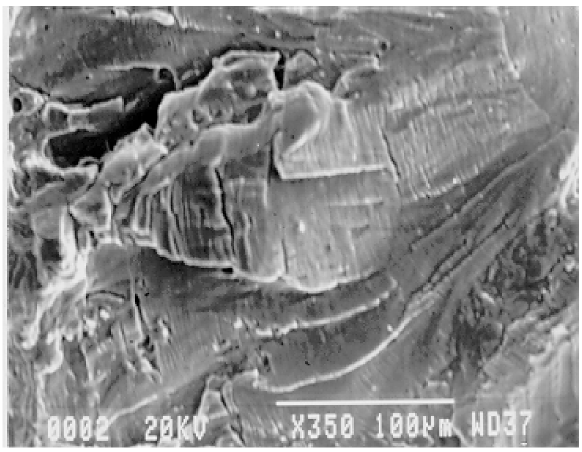

Figure 10. Fracture surface in Al- Alloy, aged for 6 h at 560 K.

Figures 2 to 4 confirm that the fatigue resistance behavior of the alloy increases with the increase in aging temperature and time. The alloy gains its maximum resistance to fatigue failure at 460K when aged between 4 to 5 hours. Further increase in aging time and temperature causes a reduction in the number of cycles to fail. The initial increase in the number of cycles to fail between 320K - 460K could be explained by vacancies assisted diffusion mechanism (Onurlu and Tekin, 1994). In the precipitation heat treatment process, during quenching of the alloy from 793K to room temperature, a super-saturated solid solution is formed which contains a large number of vacancies. At room temperature, as well as at higher temperatures, these vacancies are highly mobile and produce GP zones, which are very rich in solute atoms. At high temperatures (460K to 480K) the density of the GP zone also increases, as a result, a distortion of the lattice planes within the zone and are extended to several atomic layers in the matrix. This distortion of lattice plane causes hindrance to the dislocations movement (Jiang *et.al*,1990 b). Therefore the fatigue resistance property of the alloy is improved in the under aged to peak aged temperature. The second reason for the increase in resistance to fatigue fracture behavior of the alloy is due to pinning and hinderance of dislocation movement by impurity atoms (Blaz and Evangelista ,1996; Jiang *et.al*, 1991).

Figure 2 to 4 also show a reduction in the number of cycles to fail in this alloy when heated for a longer period of time at higher temperatures. A decrease in the number of cycles to fail above 460 and 480K can be attributed to the coalescence of precipitates into larger particles which cause less obstacles to the movement of dislocations; hence the fatigue failure occurs in a short a period of time.

4. Conclusion

The fatigue resistance property of 6063 aluminum alloy is very much dependent on the precipitation hardening time and temperature. The initial increase in fatigue resistance behavior is due to an increase in density of the GP zones and distortion of lattice planes both within the zones and in the matrix. It is also due to the increase in the number of atomic impurities which cause hinderance to the dislocations movement. Hence the fatigue resistance property of the alloy is improved. A decrease in the number of cycles to fail in the over aged alloy at 480K, and temperatures above is due to the coalescence of the precipitates into larger particles, bigger grain size and also due to annealing of defects in the lattices which cause less obstacles to the movement of dislocations. From the experimental work it is concluded that the best precipitation temperature is 460 K when 6063 aluminum alloys is aged between 4 to 5 hours. These conclusions are further supported by the SEM micrographs showing mixed mode of fracture consisting of striations as well as cleavage steps when the alloy was over aged.

References

ANDERSON, W.A. 1959. Precipitation Hardening Aluminum Base Alloy, in: *Precipitation from Solid Solution, American Society for Metals*: 150-207.

BLAZ, L and EVANGELISTA, E. 1996. Strain Rate Sensitivity of Hot Deformed Al and Al-Mg-Si Alloy, *Materials Science and Engineering A*, **A 207:** 192-201

HELBY, M. 1993. Aluminum Extrusion A Flexible Approach to Construction, *Materials World*, **1:** 101-102.

HUNSICKER, H.Y. 1967. *Metallurgy of Heat Treatment, Aluminum*, American Society for Metals, Metal Park, Ohio, **1:** 109-161,

JIANG, D.M., HONG, B.D. and LEI, T.C. 1990 a. Fatigue Fracture Behaviour of an Under aged Al-Si-Mg Alloy. *Scripta Metallurgica*, **24:** 651-654.

JIANG, D.M, HONG, B.D. and LEI, T.C. 1990 b. Influence of Composition and Dispersoid on Fatigue Fracture Behaviour of Al-Mg-Si Alloys, *Acta Metallurgica Sinica*, **26(5):** A388-A390

JIANG, D.M., HONG, B.D. LEI, T.C., DOWNHAM, D.A. and LORIMER, G.W.1991. Influence of Aging Condition on Tensile and Fatigue Fracture Behaviour of Aluminum Alloy 6063, *Material Science and Technology;* **7:** 1010-1014.

MUSULIN, I. and CELLIERS, O.C. 1990. Role of Manganese in 6063 Alloy and Effect of Quench Sensitivity in 6063. Light Metal Proc. 119 TMS Annu. Meet. Publ. by Minerals, Metal and Materials, *Metal and Material Soc*. (TMS), Warrendale PA, USA, 951-954.

OKORAFOR, O.E. 1991. Effect of Heat Treatment on the Corrosion Resistance of 6063 Aluminum Alloy, *Corrosion Prevention and Control* **38(6):** 141-144.

ONURLU, S., and TEKIN, A. 1994. Effect of Heat Treatment on the Insoluble Intermetallic Phase Present in an AA 6063 Alloy. *Journal of Material Science*, **29(6):** 1652-1655.

THORNTON, P.A. and COLANGELO, V.J. 1985. *Fundamentals of Engineering Materials*, Prentice-Hall International, pp 450-460.

VAN DEN AVYLE, J.A. and SUTHERLAND, H.J.1988. Fatigue Characterization of a VAWT Blade Material, Eight ASME Wind energy Symposium, Houston, TX, USA, 22-25 January, ASME, *Solar Energy Division (Publication)* SED , **7:** 125-129

ZAJAC, S., HUTCHINSON, B., JOHANSON, A., GULLMAN, L.O. and LAGNEBORG, R. 1993.Microstructure Control and Extrudability of Aluminium-Mg-+++Si Alloys, Micro alloyed with Manganese, *Journal De Physique*. **3(7):** 251-254.

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