LOCALIZED SHEAR BANDS IN EXPLOSIVELY BONDED

ALLOY 718/COPPER/ALLOY 718 LAMINATES

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Abstract

Explosive bonding of Alloy 718 to copper (C107) plates is used to fabricate Alloy 718 /copper /Alloy 718 laminates (12.7 mm to 19 mm thick) for the coils of advanced electromagnets. Explosive bonding leads to liquid-like flow of the copper/Alloy 718 interface as a result of high local pressure and temperature. A wavy interface is created leading to the formation of localized shear bands in Alloy 718 at the apex of the interface ripples. The microscopic shear bands in Alloy 718 are characterized by metallography. The effects of these shear bands on the mechanical behavior of the laminates have been investigated at room temperature and at 77K. The mechanisms of fatigue crack initiation and crack growth are also reported.

Introduction

Explosively bonded Alloy 718/copper/Alloy 718 plate laminates are proposed as the material for the conductor in the central solenoid coils for the Compact Ignition Tokamak (1) in order to achieve a good combination of electrical conductivity and mechanical strength. The explosive bonding process creates a metallurgical bond between two dissimilar metals by combining localized high pressure and high temperature from a collision between plates which have been accelerated by the detonating energy. Although numerous investigations about the explosive bonding process have been performed (2-4), no work has been reported about the metallurgical and mechanical behavior of the Alloy 718/ copper interface. This paper deals specifically with the shear bands in Alloy 718 at the explosively bonded Alloy 718/copper interfaces and with their effects on the mechanical behavior of the laminate.

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Alloy 718/Copper/Alloy 718 Laminates

The Alloy 718 for this application was first annealed at 940^oC, followed by a double aging heat treatment at 720^oC and at 620^oC. The oxygen free, silver bearing C107 copper (with silver content of 0.078 wt %) was cold worked to 40% before bonding. Two plates of Alloy 718 with one plate of copper in between were explosively bonded together to become a sandwich-type laminate. Laminate with different copper/Alloy 718 volume ratios (1:1, 1.222:1, 1.5:1) were produced. The total thickness of the laminates ranges from 12.7 mm to 19 mm. Metallography of cross sections of the laminates was performed. The microhardness profile across the interface of a laminate was also measured.

The three dimensional configuration of a laminate is schematically shown in Figure 1(a). The Alloy 718/copper interfaces consist of ripples produced from the explosive process. The ripples are always perpendicular to the direction of propagation of the explosive wave. The thickness of the ripples,a, measured from peak to peak depends on explosion parameters such as quantity and distribution of explosive as well as the gaps between plates. For the case of one side explosion the interface ripples on one side are thicker than on the other side because of the difference in collision energy. The interface ripples in Alloy 718 are found to be usually accompanied by shear bands at the apex of the ripples (see Figure 2) and shear band cracks inside the shear bands if the shear bands are sufficiently severe (see detailed discussion in next section). The orientation of the shear bands is characterized by the shear band angle θ, defined in Figure 1(b), and the ripple angle α, defined as the angle between the shear bands and the plane normal to the applied stress (see Figure 1).

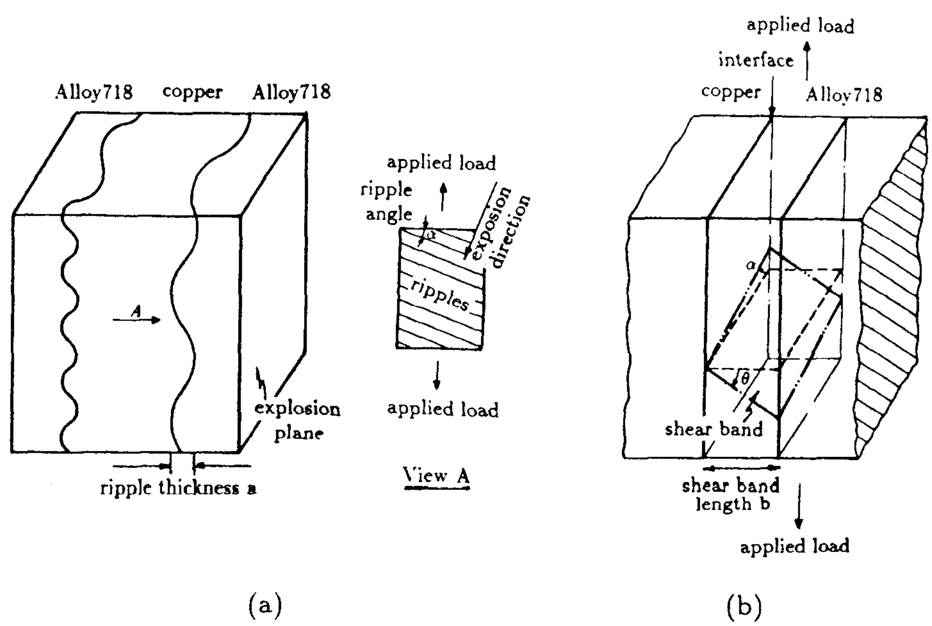


Fig. 1. Configuration of Alloy 718/Copper/Alloy 718 laminate.

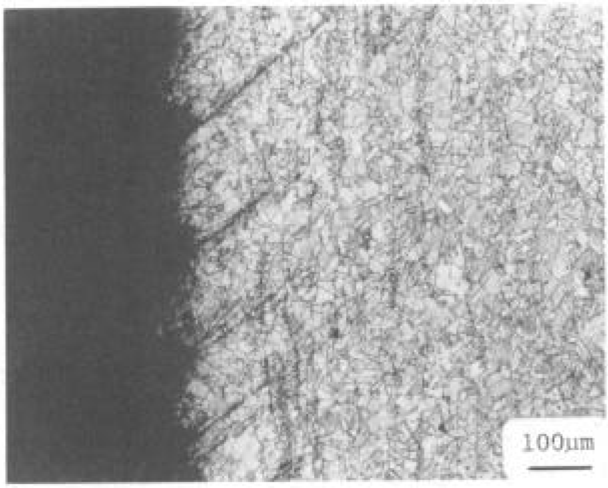


Fig. 2. Alloy 718 ripples and the associated shear bands at the apex of the ripples (dark left side is copper).

If we define a shear band length as the projected length of a shear band in the direction perpendicular to the interface, and define the shear band crack length as the sum of the projection of crack length segments (measured at 500X by optical microscopy), it is found that the shear band lengths and the shear band crack lengths decrease with decreasing interface ripple thickness (Figure 3). The shear band cracks disappear when the interface ripple thickness is less than about 0.1 mm. This data was used to set an upper limit for ripple interface thickness for development of explosion parameters and an acceptance criteria for bonded plates. This limit may require alterative if materials with different base properties were used.

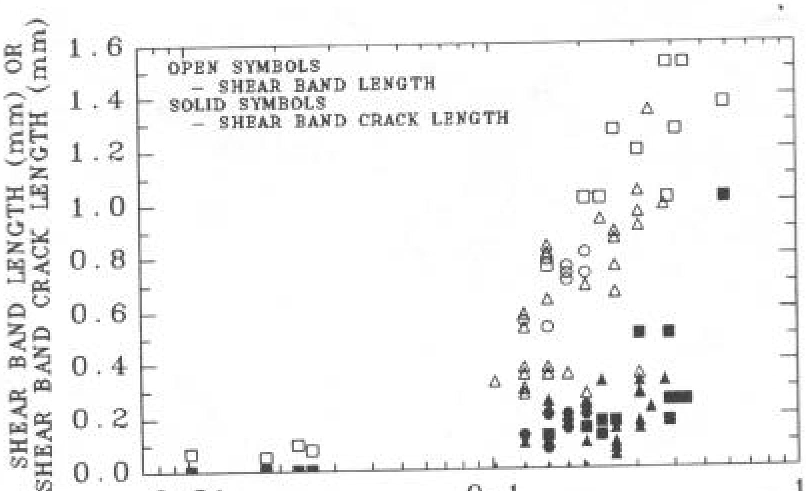


Fig. 3. Shear band length and shear band crack length as functions of ripple thickness (square, circle and triangle represent copper/Alloy 718 volume ratios of 1, 1.22, 1.5 respectively).

Measurements of microhardness HK (with 50g load and 13 seconds time delay) across the Alloy 718/copper interface are shown in Figure 4. The microhardness of the copper and of the Alloy 718 increases near the interface. The Alloy 718 has a higher microhardness at the interface than in the bulk because of its severe plastic deformation during explosive bonding (Figure 5).

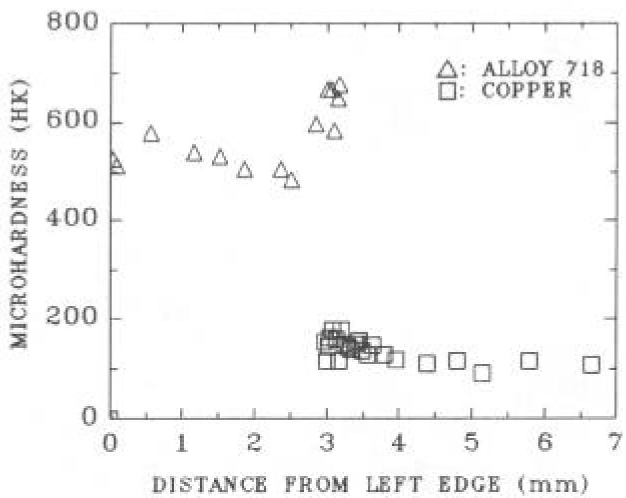
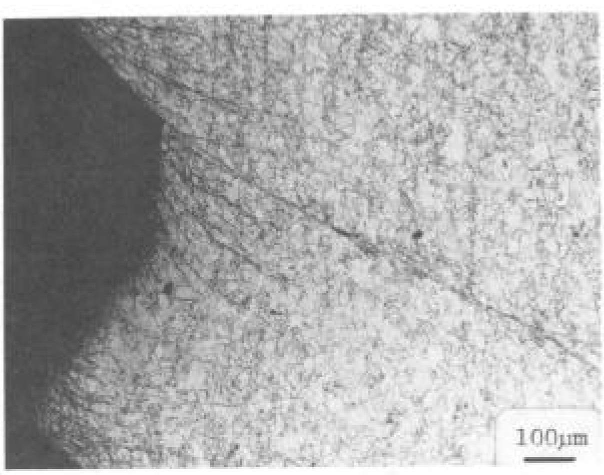


Fig. 4. Variation in micro hardness at Copper/ Alloy 718 interface.



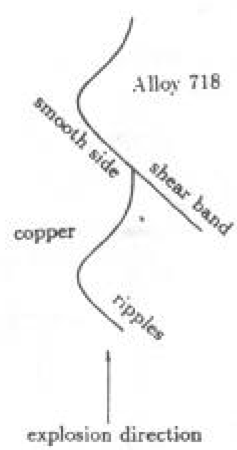


Fig. 5. Optical micrograph of the multiple shear bands at the apex of a ripple.

Shear Bands and Shear Band Cracks

The black lines at the apex of the ripples in the Alloy 718 in Figure 5, which are sweeping through all grains in the direction parallel to the smooth sides of ripples, are shear bands formed by plastic shear in the explosive process (2,3,4). The shear displacements are observed clearly in the SEM photo in Figure 6 (the arrow indicates a sheared grain). The shear band length gradually decreases with increasing distance from the smooth side of the ripple (probably the major shear plane). The shear bands can only be observed after etching with Kalling's solution. Figure 7 shows a segment of the shear band and the adjacent plastically deformed grains.

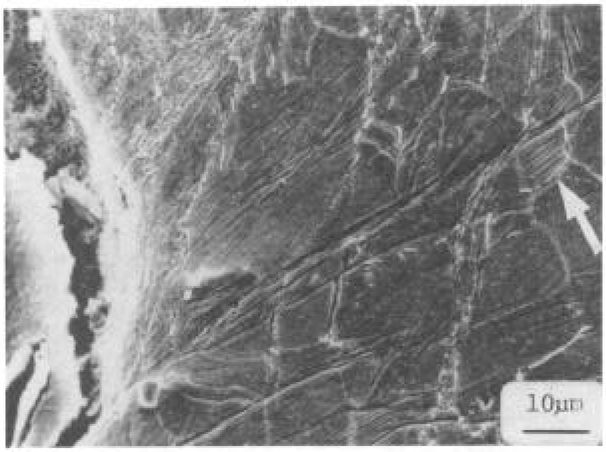


Fig. 6. Scanning electron micrograph of a shear band at the apex of a ripple; the arrow indicates a sheared grain.

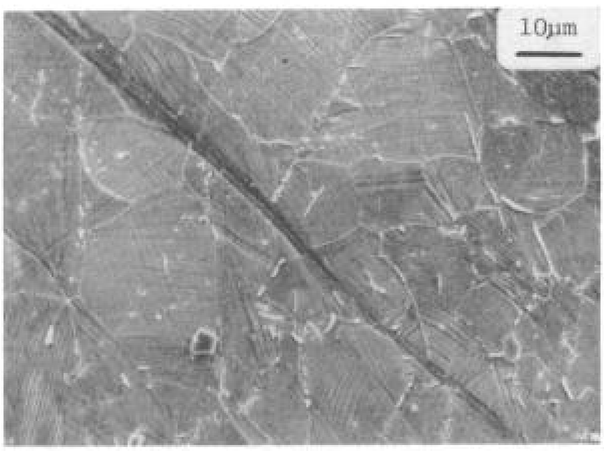


Fig. 7. Scanning electron micrograph of a deformed area adjacent to a segment of a shear band.

Although shear bands can only be observed after etching, shear band cracks can be observed in the shear band before etching (Figure 8(a)). These shear band cracks are pancake-type cavities distributed along the shear bands. The details of a shear band crack are shown in Figure 8(b). Some shear bands which opened up after fracture were examined by scanning electron microscopy. The fracture surfaces show a mixture of small shiny facets and small ductile regions (Figure 8(c)). The shiny areas seem to be amorphous as if they were produced by rapid solidification after melting.

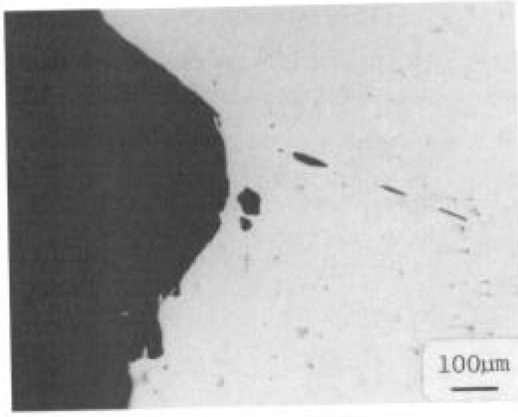
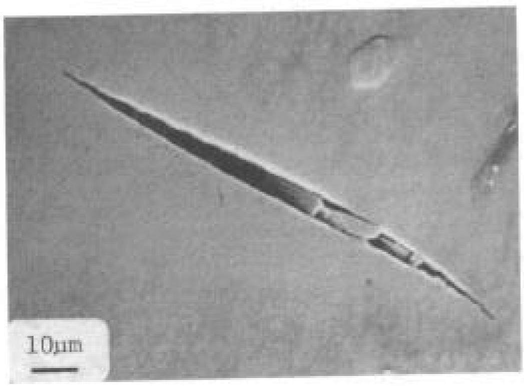
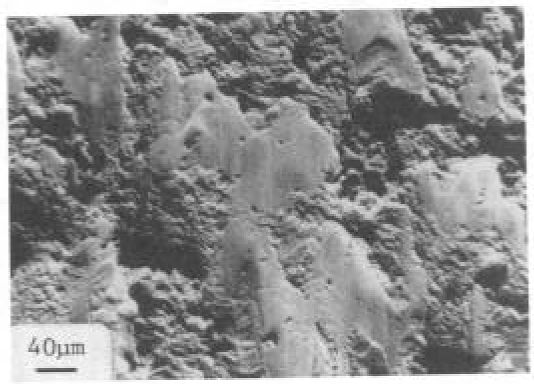


Fig. 8. Shear band crack
(a) Optical micrograph of multiple shear band cracks in a shear band before etching.





(b) Scanning electron micrograph showing a shear band crack with the broken materials inside.

(c) Fracture surface of an opened shear band.

Effects of the Shear Bands on the Mechanical Properties

The shear bands and their interaction with a load parallel to the laminate are characterized by the ripple angle α, the shear band angle θ (a constant about 35°) and shear band length b. Assuming that the shear bands are equivalent to real cracks, a theoretical analysis shows that the stress intensity factors, K_I and K_{II}, at the tip of a shear band are proportional to the square root of the shear band length, $\sqrt{b}$, and to the square of the cosine of the ripple angle, $\cos^2\alpha$, for a load being applied parallel to the interfaces of the laminate (5).

A tensile specimen for a laminate is shown in Figure 9. The results of the tensile tests at room temperature and at liquid nitrogen temperature for the laminates with different shear band orientations and ripple thicknesses are listed in Table 1. The parameter f_b (shear band fraction), measured as the ratio of shear band area to total area along the interface of a fracture surface, represents the degree of the shear band involvement in the

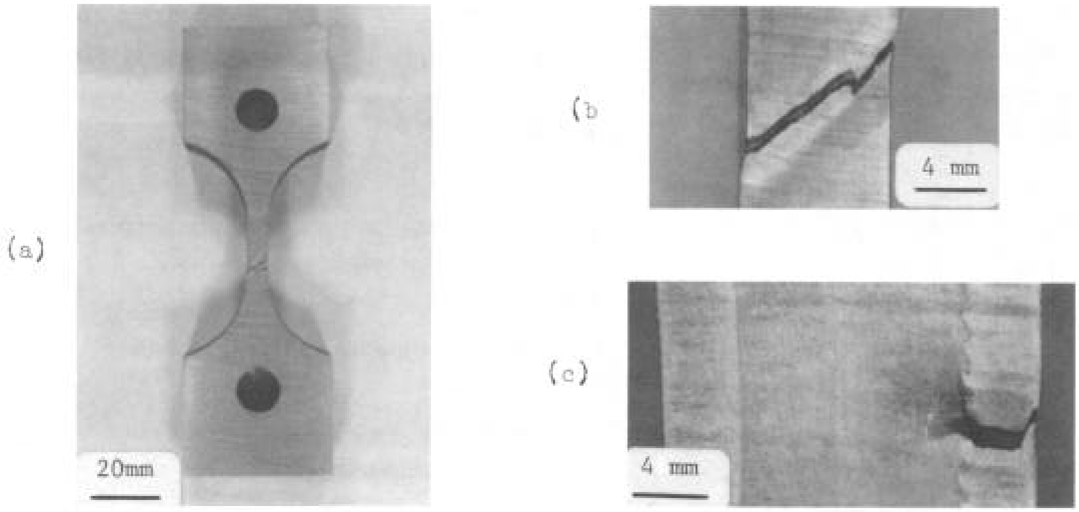


Fig. 9. (a) A tensile specimen of Alloy 718/Copper/Alloy 718 laminate with a crack at the large ripple interface.
(b) and (c) show the magnified crack.

Table 1[1,2,3]

Tensile Test Results

Specimen #	Ripple Angle α (°)	ShearBand Fraction f_b(%)	Yield Strength $\sigma_{0.2}$(MPa)	UTS (MPa)	Uniform Elongation (%)
1	10	100	754	931	0.82
2	55	100	604	765	1.01
3	63	100	576	685	0.84
4	90	0	709	992	4.5
5	56	80	795	1140	15.5

1. Copper/Alloy 718 volume ratio is 1:1, except specimen #2 where it is 1.5:1

2. Test temperature is 300 K except for specimen # 5 for which it is 77 K

3. Maximum ripple thicknesses range from 0.41 mm to 0.51 mm

fracture process. It is found that at room temperature as the ripple angles are less than about 60 degree, the shear bands control the fracture process (f_b is large), and the uniform elongation of the laminate specimens is only about 1%. For the specimens with a ripple angle of 90, there is a negligible shear band effect in the fracture process ($f_b = 0$), and the uniform elongation is as high as 4.5%, showing a more ductile tensile behavior. For the former case, cracks were found to start at the shear bands in the Alloy 718 interface with the largest ripples and propagate along the shear bands (see Figure 9), a fast fracture of the remaining cross section of the laminate followed in a shear mode.

The above observations indicate that the shear bands play a significant role in the tensile behavior of laminates when the ripple orientations are close to the perpendicular direction of the applied stress ($\alpha \leq 60°$). In this case the stress intensity factors, K_I and K_{II}, approach the maximum possible values, shear band cracks open at a certain load, and the fracture paths prefer to go through the shear bands. The only tensile specimen without an effect of shear bands is the one with a ripple angle of 90°. In this case the ripples are parallel to the applied stress direction and the stress intensity factors at the tip of the shear bands, K_I and K_{II}, are zero. There are not enough data to describe the shear band effect on the tensile behavior of the laminates at 77 K, but the uniform elongation of a laminate specimen (one test) with the shear band angle of 56° is surprisingly high at 77 K (15.5%) in comparison with that at room temperature (0.84%). This indicates a marked improvement of the strengths and ductility of Alloy 718 at low temperature.

Fatigue tests of the laminates were performed, using the geometry of the tensile specimen, at a load ratio of 0.1, and a frequency of 0.2 Hz to 10 Hz, at both room temperature and 77 K. Figure 10 shows that the fatigue life of the laminates increases as the ripple angle increases, in which applied stress is the average stress over the laminate cross section. The scattering of data is due mainly to the ripple thickness effect, a large ripple (thus a large shear band) gives a shorter fatigue life and vice versa.

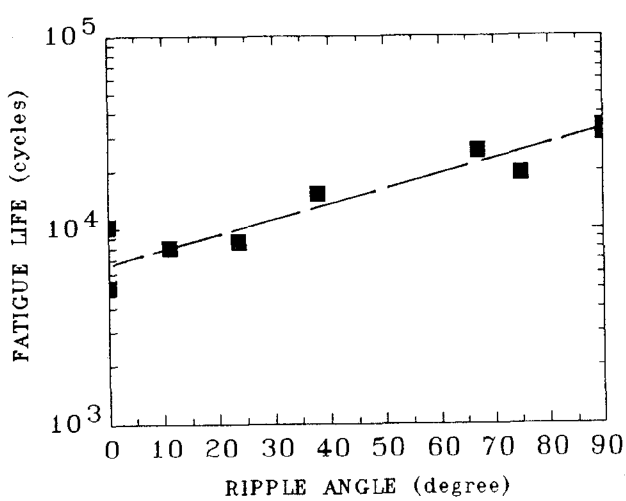


Fig. 10. Fatigue life as a function of ripple angle for an Alloy 718/ Copper/Alloy 718 laminate. Copper/Alloy 718 volume ratio = 1.5, maximum stress = 517 MPa, load ratio = 0.1, room temperature.

Failure analysis shows that the fatigue cracks initiate at the Alloy 718/copper interface, where the copper is fully plastic and the plastic strain in the copper at the interface depends upon the stress level in the Alloy 718 at interface. It is higher at the interface than in the bulk of the Alloy 718 due to the ripple notches and the shear bands. The examination of the fracture surface revealed that the fatigue cracks in Alloy 718 grow along the shear bands at any shear band angles up to $\alpha = 60^{o}$. The effects of shear bands on the fatigue behavior of the laminates at 77 K is approximately the same as that at room temperature although the fatigue lives are significantally greater at the low temperature. A more detailed discussion of the fatigue behavior of the laminates will be presented elsewhere (5).

Conclusions

(a) Shear bands and shear band cracks are formed in Alloy 718 at the interface of Alloy 718/copper/Alloy 718 laminates by the plastic flow caused by the high local temperature and pressures generated in the explosive bonding process. The shear band cracks, which exist for the shear bands with shear band lengths greater than 0.1 mm, are made up of pancake-type cavities.

(b) The length of shear band cracks, b, increases as the shear band length increases and as the thickness of the ripple interface increases.

(c) The ripple interfaces are mainly characterized by the ripple thickness ,a, the shear band length,b, and the ripple angle,α. The stress intensity factors, K_I and K_{II}, at the tip of a shear band are proportional to $\cos^2\alpha$ and $\sqrt{b}$.

(d) The shear bands have a significant effect on the mechanical behavior of the laminates if the ripple angles are less than about 60 degree. The shear bands promote a brittle behavior in the tensile specimens of the laminates. They also significantly reduce the fatigue life of the laminates as the ripple angle decreases and the shear band length increases by promoting the initiation and the propagation of fatigue cracks at the Alloy 718 interfaces.

(e) These conclusions are based on the examination of the samples with relatively large ripple thicknesses. The correlation of large ripple with more severe shear bands and cracking implies a desired upper limit on ripple thickness, which must also depend on base material properties.

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