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Coefficients of friction of YBCO–YBCO and YBCO–Ag ball-on-flat couples

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The coefficient of friction of polycrystalline $YBa_2Cu_3O_{7-x}$ (YBCO) on YBCO and YBCO on Ag was measured versus temperature and humidity in a ball-on-flat linear reciprocating experiment. The coefficient of friction as a function of strokes has initial and steady state values. In laboratory air, the average coefficients of friction of the YBCO–YBCO couple in the steady-state show a maximum of 0.90 at 100 °C, while those for YBCO–Ag show a minimum of 0.26 at 400 °C. The coefficient of friction of the YBCO–YBCO couple at 100 and 200 °C exhibits a transition as the humidity increases. This transition is associated with cylindrical wear debris.

1. Introduction

There is a good deal of interest in the mechanical processing of oxide superconductors such as $YBa_2Cu_3O_{7-x}$ (YBCO) into wires, tapes or coils because these geometries offer the possibility of commercialization of superconductors into useful components. Rolling, drawing, swaging and variations of these processes at room or elevated temperatures have been used extensively in a powder-in-tube method to produce wires and tapes. These mechanical deformation processes involve friction between the YBCO powder particles as well as between the particles and Ag as the wire cross-section is reduced. Therefore, an understanding of friction at elevated temperatures in gaseous environments is key to developing the mechanical processing of high-T_c superconductors into useful shapes.

Mechanical deformation can induce shear, compression, and tensile stresses between YBCO–YBCO and YBCO–Ag couples and therefore fracture of the superconductor grains. Parameters such as the coefficient of friction, fracture toughness and hardness are important parameters which influence the deformation and the superconducting properties.

YBCO is a brittle material with a microhardness of 4–10 GPa and a fracture toughness of 0.7–1.0 MPa m$^{1/2}$ [1–3]. Coefficients of friction of YBCO–YBCO and YBCO–Au couples vary from 0.12 to 1.0 and 0.15 to 1.1, respectively, when measured by ball-on-disc tests [4]. Abrasion was found to be linearly proportional to the normal load, and the wear rate in a pin-on-disc test was in a range of 7×10^{-2} mm^3 N^{-1} m^{-1}. Furthermore, Verkin *et al.* [5] found that the coefficient of friction decreased with increasing load: it varied from 0.3 to 0.2 for loads between 2.5 and 15 N at 273 K, and decreased to 0.1 and 0.02 for loads from 2.5 to 25 N, respectively at 77 K.

None of these studies were concerned with the coefficient of friction at the elevated temperatures or chemically reactive environments which would be expected to occur in typical manufacturing processes. This paper summarizes the results of a study of the coefficient of friction of YBCO–YBCO and YBCO–Ag ball-on-flat couples versus the temperature and humidity, as an attempt to simulate such processing. The ball-on-flat geometry is also intended to simulate powder-in-tube processing under conditions where the stresses are known and the coefficients of friction are measured *in situ*.

2. Experimental procedure

The YBCO powder was made from Y_2O_3, $BaCO_3$ and CuO using vacuum calcination at 800 °C for 6 h in flowing O_2 with a total pressure of 2670 Pa. The powder was screened, sieved and compacted at a pressure of 70 MPa into a series of pellets. The pellets were placed in Al_2O_3 crucibles, sintered at a temperature of 990 °C for 6 h and oxygenated at 450 °C for 10 h under flowing O_2. The density was approximately 95–97% of the theoretical density (6.3 g cm^{-3}) after sintering. Typical sintered samples exhibited a transition temperature at $T_c = 91$ K, with superconducting quantum interference device (SQUID) measurements.

YBCO pellets were sectioned into rectangular shapes, and the ground surfaces were polished by standard metallographic techniques down to a 0.1 μm Al_2O_3 powder slurry using ethyl alcohol as a lubricant. Except for using water as a lubricant, a similar polishing procedure was used for the Ag specimens. YBCO spheres were fabricated by a cup grinding process [6]. A poly-sided geometrical shape of YBCO was cut from a pellet, polished into a polyhedron shape with an abrasive grit, and then final polished down to 0.1 μm Al_2O_3 powder on top of a steel tube positioned on a polishing wheel. The diameter of the YBCO balls was 6.35 mm. The specimens were cleaned with alcohol in an ultrasonic bath and kept in a desiccator until required.

The friction experiments were conducted by inserting and clamping the flat specimen on a specially machined ceramic rod, securing the ball in a fixture, and adjusting the load from 2.2 to 5.0 N on the ball. The flat specimen was moved in a straight line beneath the ball by a linear reciprocating motion during the test. The dead load, velocity and stroke length were fixed and the temperature of the furnace was set to a predetermined value. The humid environment was produced by bubbling reagent-grade air through a water bath and saturating the air at a controlled temperature to fix the water vapour content of the gas mixture. The flow rate of the compressed air was between 3700 and 4000 $cm^3 min^{-1}$. The frictional force between the ball and the plate was measured by a transducer and stored by a minicomputer. The sampling rate of the computer was two to eight data points per second, and these signals were converted to forces and printed out as coefficients of friction with an average of every 400 data points.

3. Results

3.1. Coefficients of friction

Typical coefficients of friction of YBCO–YBCO and YBCO–Ag couples as a function of the number of strokes at elevated temperatures for a load of 2.2 N in laboratory air are shown in Figs 1 and 2, respectively. Each point in these figures represents an average of 400 data points within 20 (sliding speed = 2.0 $cm s^{-1}$) or 16 (sliding speed = 1.3 $cm s^{-1}$) cyclic strokes.

The coefficient of friction changes with the number of strokes and the behaviour can be subdivided into two regions:

1. Initial state (break-in): the coefficient of friction varies with the number of strokes due to the initial surface roughness, area of contact and other parameters. These figures show that the break-in period is approximately 1500 strokes and this break-in period was shorter as the temperature increased.
2. Steady state: the coefficient of friction reaches a constant value after a certain number of strokes and remains at this value for the rest of the test. The fluctuation of the coefficients of friction of YBCO–YBCO and YBCO–Ag couples in the steady state is less than 15%.

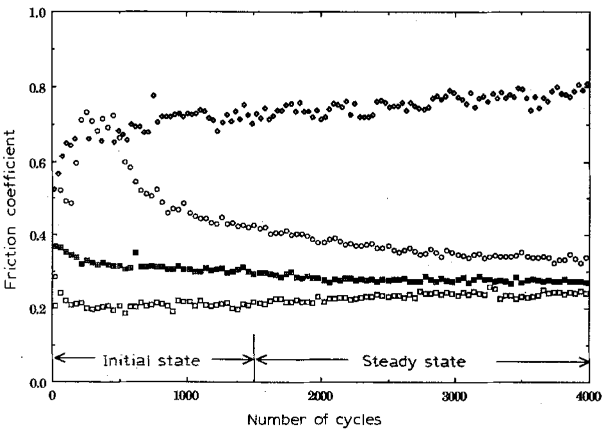

Figure 1 Coefficient of friction versus the number of strokes for the YBCO–YBCO couple in laboratory air for a constant load of 2.2 N: (○) $T = 25\,°C$, $V = 2.0$ cm s^{-1}; (◇) $T = 200\,°C$, $V = 1.3$ cm s^{-1}; (⊞) $T = 400\,°C$, $V = 2.0$ cm s^{-1}; (□) $T = 700\,°C$, $V = 2.0$ cm s^{-1}.

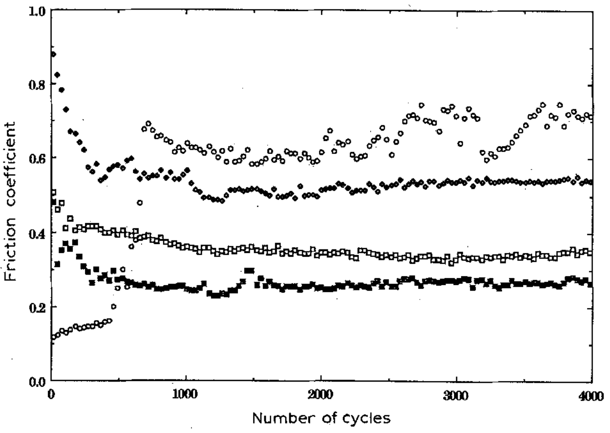

Figure 2 Coefficient of friction of the YBCO–Ag couple versus the number of strokes at a load of 2.2 N and speed of 1.3 cm s^{-1}, in laboratory air: (○) 25 °C, (◇) 200 °C, (⊞) 400 °C, (□) 600 °C.

The length of the initial state and the beginning of the steady state region varied with temperature. At room temperature, the coefficient of friction of the YBCO–YBCO couple is 0.29 at the beginning of the test, increases to a maximum value of 0.73 at about 300 cycles, then decreases with the number of strokes to a steady state value of 0.35 after about 1500 cycles, as shown in Fig. 1. This result is very similar to that of a previous report by Blau *et al.* [4]; they reported a coefficient of friction of 0.15 at the beginning of the test, reaching a maximum of 0.8–1.0, and settling to about 0.6 at the end of the test. In the other cases, the coefficients of friction of YBCO–YBCO and YBCO–Ag change monotonically with stroke cycles.

Fig. 3 shows the average steady state values of the coefficients of friction as a function of temperatures for both the YBCO–YBCO and YBCO–Ag couples in laboratory air. Error bars with 95% confidence intervals were estimated by the t-distribution from five to six repeated experiments. Coefficients of friction of the YBCO–YBCO and the YBCO–Ag couples dropped when the temperature increased over 300 °C, by a factor of 2.5 from a maximum value of 0.82 at 25 °C to a minimum value of 0.26 at 400 °C for the YBCO–Ag couple. However, the coefficient of friction of the YBCO–YBCO couple changes from a value of 0.35 at room temperature to a maximum of 0.90 at 100 °C, then rapidly falls to a constant value at temperatures higher than 400 °C. Above 400 °C there is a continual decrease of the coefficient of friction because of the formation of debris.

Fig. 4 shows the average steady state coefficients of friction as a function of humidity at 100, 200 and 400 °C. Although these data are limited, there appears to be evidence for a transition of the coefficient of friction with the humidity. At 100 °C, the coefficient of

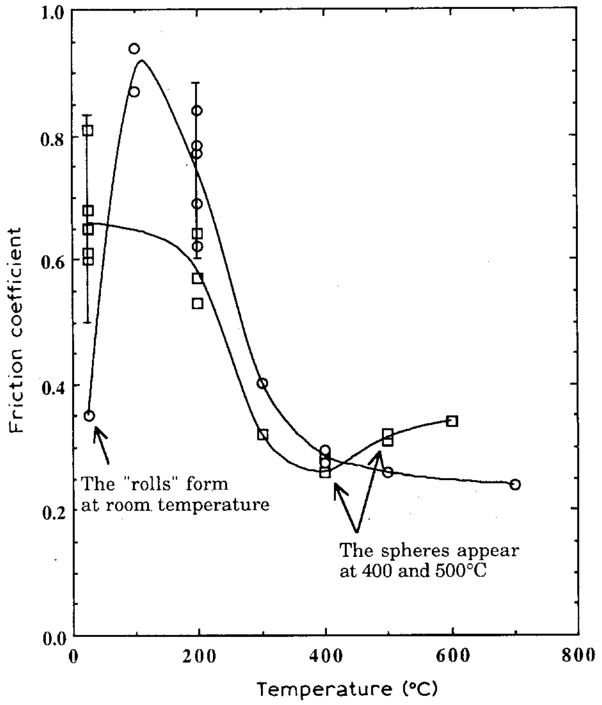

Figure 3 Coefficients of friction of (□) YBCO–Ag and (○) YBCO–YBCO couples in the steady-state versus temperature in laboratory air. Normal force = 2.2 N, stroke length = 2.0 cm, sliding speed = 1.3–2.0 cm s^{-1}.

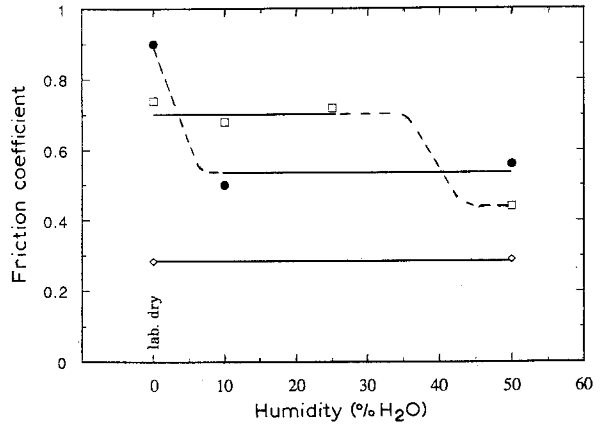

Figure 4 Coefficient of friction (steady-state value) of the YBCO–YBCO couple as a function of the humidity at elevated temperatures: (●) 100 °C, (□) 200 °C, (◇) 400 °C.

friction decreases from 0.9 in laboratory air to 0.5 in the 10–50% humid environment. At 200 °C, the transition occurs in the range between 25% H_2O–air and 50% H_2O–air. At 400 °C, a transition was not observed and the coefficient of friction remained constant at 0.3 for the two tested humidity levels.

3.2. Wear microstructure

Scanning electron microscopy was used to examine the wear surfaces. In laboratory air, the morphology of the wear track of the YBCO–YBCO couple is completely different for tests performed at room temperature as compared with temperatures higher than 100 °C. At room temperature, the coefficient of friction decreases with an increase in the number of strokes after about 500 cycles and this is believed to be related to the geometry of the wear debris. In this case, the debris is in the form of "rolls". This phenomenon only appears in tests at room temperature in the laboratory air or at 100 and 200 °C in the humid air environment, and has also been reported by Blau *et al.* [4] at room temperature.

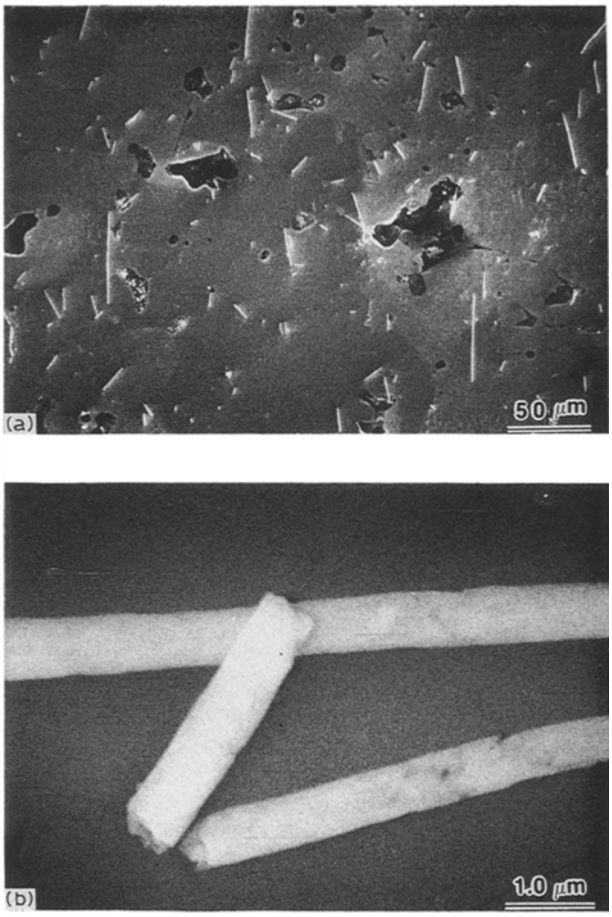

Figure 5 Scanning electron micrographs of the rolls on YBCO specimens: (a) rolls on the wear groove of YBCO plate, (B) the same at high magnification.

Fig. 5 shows a series of micrographs of the YBCO wear track produced at room temperature after 4000 strokes. These micrographs show the morphology of the "rolls". The rolls have cylindrical shapes with diameters of about 0.8 μm, and are oriented approximately perpendicular to the sliding direction. In some cases the rolls have broken into smaller pieces, as shown in the higher-magnification micrograph. The rolls also appear in the wear region of the YBCO ball. The mean length of the rolls is 10 μm with a standard deviation of 7 μm. The mode is about 6 μm. The longest rolls are over 50 μm long.

The morphology of the wear debris of the YBCO–Ag couples was different from that of the YBCO–YBCO couples. For the YBCO–Ag ball-on-flat couple the wear debris formed at 400 and 500 °C is spherical and aligned along the sliding direction, as shown in Fig. 6. These spheres have varying sizes with an approximate diameter from 0.5 to 2.0 μm. Fig. 6b also shows that the spheres can be agglomerated, situated in the wear groove and flattened at 500 °C. The spheres only exist at temperatures between 400 and 500 °C, and disappear at higher or lower temperatures.

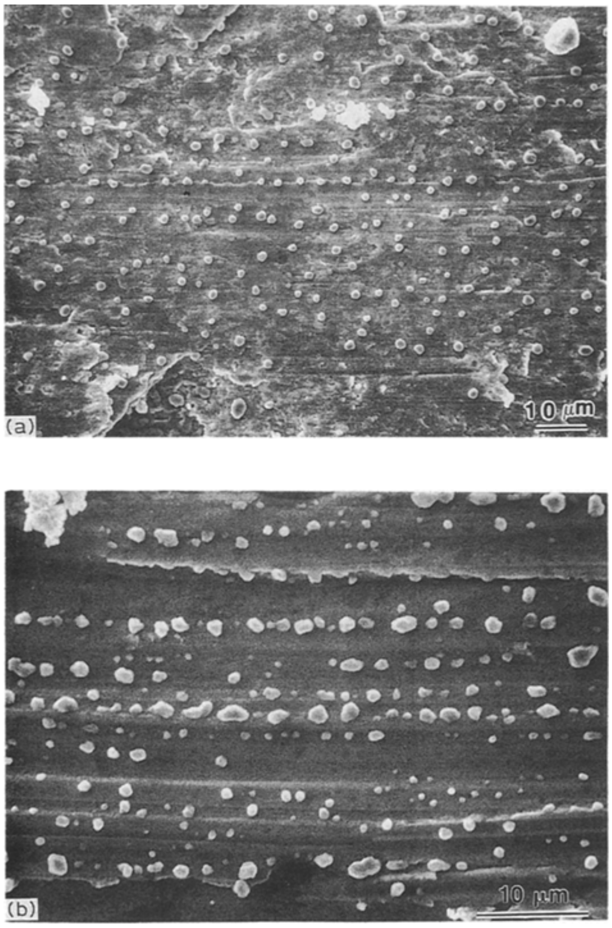

Figure 6 Scanning electron micrographs of the Ag plate: (a) spherical wear particles at 400 °C, (b) spheres at 500 °C.

4. Discussion

4.1. Variation of friction

It is well known that coefficients of friction of ceramics first decreases with increasing temperature, exhibits a minimum at a transition temperature, and then increases at high temperature. This effect has been observed in experiments with self-mated TiC, WC, ZrB_2 and SiC, and Al_2O_3–SiC couples [7, 8].

A major contribution to the coefficient of friction is humidity, which is related to surface reactions with gaseous environments. Tribochemical reactions may form surface films, and as a result, third-body materials at the contact interface. The coefficient of friction of the YBCO–YBCO couple decreases for this reason as humidity increases.

As pointed out by Yan *et al.* [9], YBCO may react with water at room temperature by the following reactions:

$$3H_2O + 2YBa_2Cu_3O_7 = Y_2BaCuO_5 + 3Ba(OH)_2 + 5CuO + \tfrac{1}{2}O_2$$

and the $Ba(OH)_2$ can react with CO_2 in the air to form a carbonate:

$$Ba(OH)_2 + CO_2 = BaCO_3 + H_2O$$

It is likely that the YBCO used in our experiments is initially covered by a $BaCO_3$ film. This film may affect the coefficient of friction so that the friction is high at the beginning of the test. As the film is ruptured and removed by the hemispherical ball, the newly exposed surface as well as wear debris react with the humid environment to re-form surface films. In addition, debris particles readily react with the water vapour due to the large surface-to-volume ratio. As water is adsorbed, the wear debris may form rolls which are responsible for the decrease of the coefficient of friction in the humid environment.

The formation of the film depends on temperature, as well as humidity. Since moisture in the laboratory environment is vapourized at temperatures above 100 °C, the film on the YBCO surface cannot be recovered after it is broken, and tribochemical reactions cannot continue during the experiment; therefore, the wear debris cannot form rolls on the wear track and the coefficient of friction of the YBCO–YBCO couple increases between room temperature and 100 °C in laboratory air. In the humid environment, the absorption tendency of water is reduced as the temperature is increased and the transition of the coefficient of friction varies with the temperature. Also, the higher the temperature, the higher the humidity required to form the rolls. As shown in Fig. 6, the coefficient of friction of the YBCO–YBCO couple dropped within 10% H_2O–air at 100 °C and this occurred in 25% to 50% H_2O–air at 200 °C.

4.2. Debris morphology

The formation of rolls from the wear debris, which is usually associated with humidity and elevated temperatures, has been observed in silicon [6], silicon nitride [8, 10], silicon carbide [11, 12] and alumina [13]. Both the coefficient of friction and the wear rate will decrease after the wear debris forms into rolls.

The roll formation of YBCO is also related to the humidity. Humidity causes a film to form, and as this film breaks due to the sliding of the YBCO ball, it may curl as a result of the residual stresses, as suggested schematically in Fig. 7. As the wear debris saturates with H_2O, small platelets form nuclei which join to form large rolls.

Although the mechanical properties and microstructure of the rolls in Fig. 5 have not yet been determined, similar rolls on silicon nitride and alumina/silicon carbide have been reported to be flexible, with an amorphous structure. Fischer and Tomizawa [11] found that in humid environments, an amorphous surface layer of about 0.3 µm thickness occurred on the Si_3N_4 couples in sliding contact. These data offer evidence that amorphous phases consisting of hydroxide compounds and OH^- ions may play an important part in roll formation. OH^- ions may attach to covalent or ionic bonds in amorphous phases which are the products of the chemical reaction between sliding materials and water vapour.

The reasons for the formation of spheres on the silver plate are not yet known. However, this kind of debris has been reported by Scott [14] and Scott and Mills [15, 16] in rolling contact. These researchers suggest that spherical particles form from tongues of the metal which are characteristic features associated with rolling contact fatigue, and that spherical debris

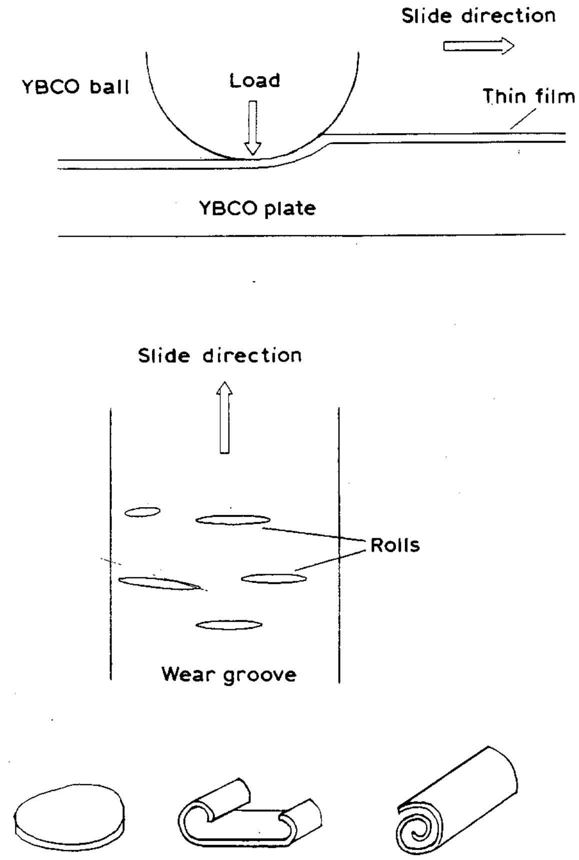

Figure 7 Schematic diagram of roll formation.

is formed by deformation processes: pieces of metal that can be severely worked and rounded by the pressure on the fracture faces, during passage of the crack over the mating bearing surfaces. Spherical particles may also be formed directly in deformed sub-surface material by sub-surface crack propagation.

5. Conclusions

The conclusions of this study may be summarized as follows:

1. The coefficient of friction as a function of stroke cycles can be divided into initial and steady states. The average coefficient of friction of YBCO–YBCO in the steady state varies from 0.90 to 0.26 depending on temperature, while that for YBCO–Ag varies between 0.8 and 0.26. The coefficient of friction exhibits a minimum at 400 °C.

2. The coefficient of friction of YBCO–YBCO at room temperature in laboratory air varies from a maximum value to a steady state value by a factor of two, and exhibits a transition at 100 and 200 °C in humid air. The transition with humidity is associated with wear debris forming the rolls.

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