Theme: Shape-Memory Alloys

MECHANICAL DAMPING WITH HIGH HYSTERESIS CU-BASE SHAPE-MEMORY ALLOYS*

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Abstract

Cu-base alloys (Cu-Zn-Al, Cu-Al-Be, Cu-Al-Ni), depending on their composition, have martensitic transformations that can be thermally or mechanically induced between a metastable structure called austenite and one or more metastable structures called martensites. In single crystals, depending on the specific composition of the alloy and the crystallographic orientation of the tensile axis, martensite-martensite transformations can be mechanically induced. The hysteresis associated to these martensite-martensite transitions is usually much greater than the one associated to the austenite-martensite transformation. Thus, martensite-martensite transitions are potential candidates for energy dissipation in a mechanical damper. Possible applications that would benefit from high hysteresis include seismic damping devices, dampers for satellites and the aerospace industry, defense and others. We present pseudoelastic cycling results of alloys submitted to different thermal treatments. Our conclusions highlight the fact that, under certain conditions, Cu-base alloys deliver better damping performance than commercially available SMAs and even the new Fe-base SMAs.

Keywords: Shape-Memory Alloys; Pseudoelasticity; Phase transformations; Damping.

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1 INTRODUCTION

1.1 The Shape-memory Effect and Pseudoelasticity

Shape-Memory alloys (SMAs) are able to return to a predetermined shape when the temperature increases a sufficient number of degrees, which depends on the specific alloy. Normally, shape-memory alloys can be deformed at low temperatures and, when they are heated, they return to their original shape.

The shape-memory effect is based on a martensitic transformation from a metastable phase, commonly known as austenite. If no mechanical stresses are applied to the alloy, when the temperature drops below a certain threshold the austenite begins to transform to a martensitic phase with a different unit cell, at a temperature called M_s. The temperature at which the martensitic transformation ends is called M_f. In shape-memory alloys, this thermally-induced transformation can be reverted, that is, the martensite can retransform to austenite when the alloy is heated: the temperature at which the martensite starts to retransform to austenite is called A_s and the temperature at which the transformation ends is called A_f. It is important to mention that the transformation temperatures from austenite to martensite are not the same as the retransformation temperatures, that is, M_s is smaller than A_f and A_s is greater than M_f. This difference between the aforementioned temperatures results in hysteresis between the transformation and retransformation of martensite, which can be measured in units of temperature (°C, for example). A similar effect, discussed below, occurs when the martensitic transformation is induced by mechanical stresses: the hysteresis between the transformation and retransformation, in this case, can be measured in units of stress (MPa, for example).

Even though the martensite is a different phase from the austenite, when the martensite is induced thermally, there is no macroscopic shape change in the material, because different martensite variants are formed from the original austenite, each with a different crystallographic orientation. The sum of the shape changes generated by each martensite variant results in a negligible macroscopic change, providing that no mechanical stresses are applied [1].

When the material is in martensite, it is relatively easy to reorient the martensite plates with the application of small mechanical stresses. This phenomenon is interesting because it changes the macroscopic shape of the material, within certain limits, without any real plastic deformation. When the load is removed, the material remains in its deformed condition but, if the alloy is heated beyond the A_f temperature, the martensite completely retransforms to austenite and the material recovers its original shape. This phenomenon is called the “shape-memory effect”.

Another interesting effect that some shape-memory alloys have is pseudoelasticity, which occurs when the alloy is kept at a temperature some degrees above A_f. Under these conditions, the austenite transforms to martensite with the application of a relatively small mechanical stress and the material deforms macroscopically. Nevertheless, when the load is removed, the mechanically-induced martensite retransforms to austenite and the material returns to its original shape. The stresses associated with the transformation are greater than the retransformation stresses, which generates hysteresis and energy dissipation by the material. The magnitude of the deformation associated to the pseudoelastic effect is much greater than the elastic deformation of the material and this phenomenon can be used in damping devices [1].

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It is interesting to mention that some Fe-base SMAs show shape memory effect but no pseudoelasticity is present, such as Fe-Mn and Fe-Mn-Si [2,3]. Recently, it has been reported that textured Fe-Ni-Co-Al-Ta-B and Fe-Mn-Al-Ni alloys shows both effects [4,5], which opens many interesting possibilities for research. However, as it is not feasible to present a complete review of mechanical damping with SMAs, the present work will focus on Cu-base SMAs, specifically on the high hysteresis 18R-6R martensitic transition, described below.

1.2 Cu-base Shape-memory Alloys

Some ternary Cu-base systems, such as Cu-Zn-Al, Cu-Al-Be, Cu-Al-Ni, for certain chemical compositions, are SMAs. In Cu-Zn-Al, the austenite is a BCC structure ordered to the second neighbors, which is called β. An important parameter for the characterization of these alloys is its electronic concentration, which is defined as the average of the amount of free electrons per atom and depends on the chemical composition. For single crystals with their axes oriented close to the [100] direction of the β phase and having an electronic concentration of 1.48, two different martensitic structures can be induced by stress: A monoclinic structure with 18 planes in its unit cell, which is called 18R, and a FCC–type structure, which is called 6R. Under traction, the β phase first transforms to 18R which can, in turn, transform to the second martensitic phase, 6R, when the strain increases. Martensitic transformation stresses are very sensitive to the chemical composition of the SMA, as the relative stability between the different phases involved also depends on the composition.

The relative stability between martensitic phases can be measured by the stresses that are necessary to induce the transformation at a given temperature. The total pseudoelastic strain that can be obtained by the β-18R-6R sequential transformation is approximately 20%, depending on the crystallographic orientation of the crystal. Hysteresis is present in both martensitic transformations and a significant amount of energy is absorbed by the material in each cycle. The pseudoelastic effect, combined with its energy damping characteristics, is very interesting to several engineering applications such as actuators, robotics, seismic damping systems, etc. However, in Cu-Zn-Al SMAs with electronic concentration of 1.48, the 6R phase deforms plastically immediately after it is formed [6]. This plastic deformation is undesirable and compromises the mechanical properties and the shape recovery capacity of the alloy. A possible solution to this problem is to increase the hardness of the 6R phase by the introduction of nanoprecipitates [7], which effectively prevents the plastic deformation of the 6R phase during and immediately after its formation.

A typical stress-strain curve of Cu-Zn-Al alloys with precipitates is shown in fig. 1. The elastic range of the β phase is clearly observed, followed by the β-18R martensitic transformation which occurs at a well-defined stress, generating a plateau in the curve. At the end of the β-18R transformation, it is possible to observe the elastic behavior of the 18R phase, followed by the 18R-6R martensitic transformation, which also generates a plateau in the curve. The crosshead movement direction was inverted before the end of the 18R-6R transformation. During load removal, the elastic range of the 6R phase is observed, followed by the 6R-18R and 18R-β martensitic retransformations. As the alloy was previously hardened by nanoprecipitates, no permanent deformation is observed at the end of the cycle. All martensitic transformations are indicated with arrows in the figure, as well as their corresponding hysteresis, shown as shaded areas.

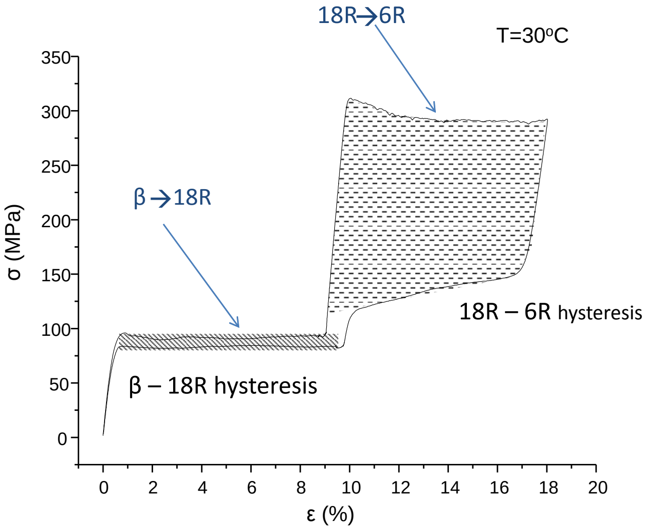

Figure 1 - typical stress-strain curve of Cu-Zn-Al single crystals, with precipitates. The martensitic transformations are shown with arrows. The shaded areas show the hystereses associated to each transformation.

From figure 1, it is clear that the hysteresis of the 18R-6R transformation is much greater than the one associated to the β-18R transformation. As energy dissipation is proportional to the hysteresis, the 18R-6R transformation is potentially advantageous for applications that require high damping.

1.3 Mechanical Damping with Shape-memory Alloys

It is possible to use shape-memory alloys as mechanical dampers due to the hysteresis associated to the martensitic transformations. Moreover, in adequately oriented Cu-Zn-Al, Cu-Al-Be and Cu-Al-Ni single crystals, it is possible to extend the deformation and increase the total hysteresis of the pseudoelastic cycle by using both martensitic transformations. This approach is very promising, providing the properties of the material remain reasonably stable.

The potential uses of shape-memory alloys in mechanical dampers for civil structures, such as buildings and bridges, to dampen the oscillations generated by earthquakes, winds, etc. has been the object of increasing interest in recent years [8-10].

The hysteresis of the pseudoelastic cycle is one of the most important factors to be considered. As a first approach, we can define the hysteresis as the difference between the transformation and retransformation stresses, even though the area of the cycle is a more accurate measure, especially if either the transformation or the retransformation stress is not constant. The greater the hysteresis, the greater will be the energy dissipated in each cycle, which leads to a more effective damper. Another important factor to be considered is the fact than the critical stresses to induce the pseudoelastic effect depend on the working temperature, according to the relationship described by the Clausius-Clapeyron equation [11]. If transformation and retransformation stresses are very sensitive to temperature changes, the dynamic behavior of the structure will also be sensitive to the temperature and the performance of the damping devices will depend on the temperature to which they are exposed. Other important parameters that must be considered are the evolution of the pseudoelastic cycles as the number of cycles increases, the number of cycles to fracture, martensite stabilization and recovery due to atomic diffusion effects, etc.

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2 MATERIAL AND METHODS

The Bridgman method was used to grow Cu-14.78at%Zn–16.61at%Al (Cu- 16.743 Zn- 7.762 Al in wt. %) cylindrical single crystals with 4.7 mm diameter. This specific composition was chosen so that the electronic concentration is e/a=1.48, as this value makes it easier to avoid the decomposition of the β phase. Moreover, for this chemical composition, the nominal 18R martensitic transformation temperature M_S = 0 ºC, so pseudoelasticity is present at room temperature. In order to minimize the 18R-6R transformation stress and, at the same time, avoid the formation of multiple martensite variants, a seed with the appropriate crystallographic orientation was used to grow the crystals. The orientation of the crystals is shown in fig. 2, along with the range of crystallographic orientations in which the 18R-6R transformation occurs.

The crystals were machined to approximately 2.5 mm diameter and submitted to one of the following thermal treatments: samples with precipitates were submitted to 30 minutes at 830ºC, cooling in air until 530ºC K and a quench in water at 5ºC. Samples without precipitates were submitted to 30 minutes at 830ºC, followed by a quench in water at 5ºC. The precipitation thermal treatment induces a uniform distribution of γ-phase nanoprecipitates and prevents the 6R phase from being deformed plastically during or immediately after its formation [7]. The samples were then mechanically and electrochemically polished, first with 600 grit sandpaper and then with a solution of 15 % nitric acid in methanol.

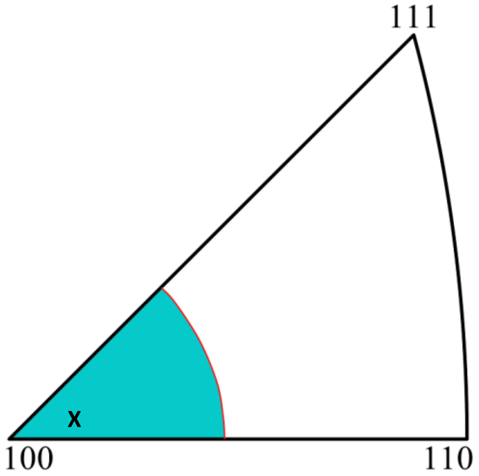

Figure 2 - Crystallographic orientation of the samples used. The 18R-6R martensitic transformation occurs in single crystals whose orientations are inside the green area.

An Instron 5567 Machine was used to test samples at 0.0025 Hz and a MTS 810 machine was used for tests at 1 Hz, which is the same order of magnitude of the frequencies expected in a building during an earthquake. The strain was measured by crosshead displacement. At 0.0025 Hz, the movement of the crosshead was driven by a sawtooth waveform, i.e., the crosshead moved at a constant speed between the lower and upper limits defined for the cycling. Whenever the crosshead reached one of the predefined limits, the direction of movement was inverted. At 1 Hz, due to inertia reasons, a sinusoidal waveform was used to drive the movement of the crosshead, i.e., the crosshead speed (and also its position and acceleration) between the cycling limits was not constant but varied according to a sine function of period 1 s.

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3 RESULTS AND DISCUSSION

3.1 Low Frequency Cycling – with Precipitates

A sample with precipitates was first submitted to low frequency mechanical cycling through the 18R-6R transformation. The results are shown in figure 3. It is clear that very strong martensite stabilization takes place in the alloy after a small number of cycles, as both the transformation and retransformation stresses decrease as the number of cycles increases. After 25 cycles, the 18R-6R transformation is significantly different from the reference cycle (cycle 2): in cycle 25, a slope in the transformation stress is clearly observed. Moreover, the slope of the 6R-18R retransformation is increased. The area of the cycle decreases somewhat, which means that there is a decrease in total hysteresis. As the number of cycles increases, both the transformation and retransformation slopes increase, and the area enclosed in the cycle decreases significantly. Both transformation and retransformation stresses drop due to cycling and, at a certain moment, the 18R-β stress is reached and retransformation to austenite begins. This phenomenon is clearly seen in cycle 100, where β-18R transformation and retransformation occurs when the strain is below approximately 12.3 %.

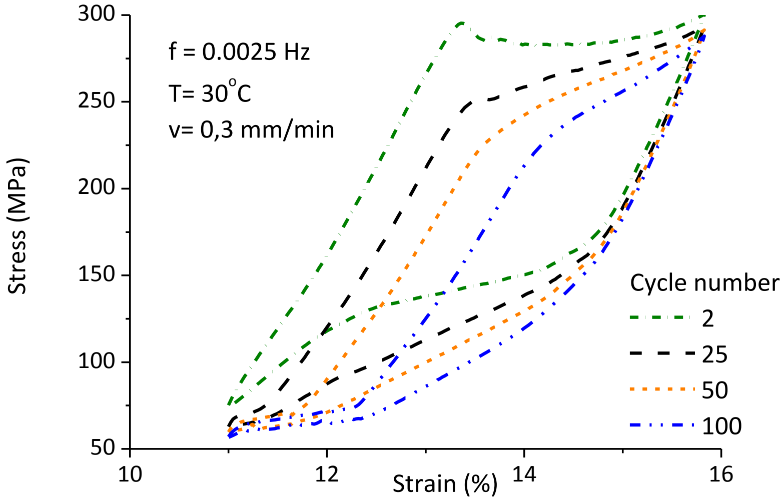

Figure 3 – low frequency cycling, with precipitates. Significant martensite stabilization is observed after a few tens of cycles.

3.2 High Frequency Cycling – with Precipitates

A fresh sample with precipitates was submitted to mechanical cycling at 1Hz through the 18R-6R transformation. The machine crosshead was used to measure strain. The results are shown in figure 4. It is clear that the behavior of the material at high frequencies is significantly different from its behavior at low frequencies: at this frequency, very little stabilization is seen in the first hundreds of cycles and it is possible to reach 1000 cycles without seriously compromising the properties of the material. In fact, at 1 Hz cycle 100 overlaps with the reference cycle almost perfectly (cycle 100 is not shown in figure 4 because of the overlap with cycle 1), whilst at low frequencies cycle 100 is already severely distorted. Some martensite stabilization is observed as both transformation and retransformation stresses decrease with the number of cycles. Moreover, a slight stress slope is seen during the transformation and retransformation.

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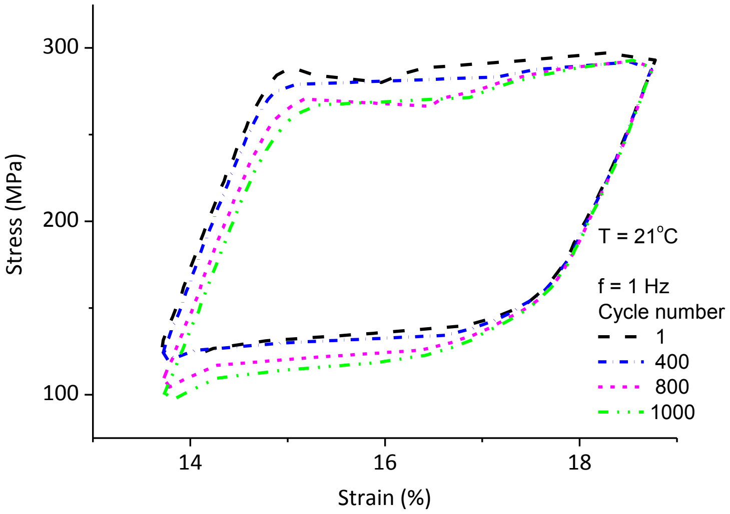

Figure 4 – high frequency cycling, with precipitates. The material is very stable and little martensite stabilization is observed, even after 1000 cycles.

3.3 High Frequency Cycling – without Precipitates

A sample without precipitates was submitted to mechanical cycling at 1Hz through the 18R-6R transformation. The results are shown in figure 5. The behavior of the material without precipitates is very similar to the behavior of the material with precipitates, which is an unexpected result. Because the 6R phase deforms plastically when it is formed, we expected the mechanical properties of the material to be worse. Similarly to the material with precipitates, very little stabilization is seen and it is possible to reach 1000 cycles without seriously compromising the properties of the material. The decrease in retransformation stresses is somewhat more pronounced than in the material with precipitates and a slope is more evident in this case.

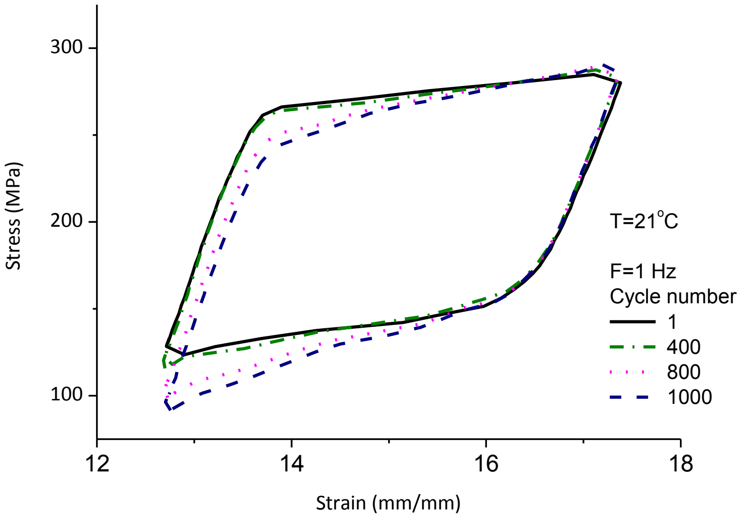

Figure 5 – high frequency cycling, without precipitates. The behavior of the material is very similar to the condition with precipitates.

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3.4 Discussion

The frequency of the mechanical cycles is a very important variable that defines the evolution of the mechanical properties of the material with the number of cycles. At low frequencies, martensite stabilization is significant after a small number of cycles, decreasing the transformation and retransformation stresses, which changes the shape of the cycles. This effect is undesirable, because the damping capacity of the material is reduced and the dynamic behavior of the structure to which the SMA damper is attached is expected to change. At the frequency studied, the material could be used in applications where only a very small number of cycles is required, but a more stable mechanical behavior is desirable.

At 1 Hz, the behavior of the material is much more stable, as it is possible to reach 1000 cycles with very little stabilization, with or without precipitates. This number of cycles is enough for certain applications, such as seismic damping, as the expected number of cycles a structure is submitted to during earthquake is well below this value. According to the results obtained, the mechanical properties of a damping system based on the 18R-6R martensitic transition in CuZnAl single crystal SMA should not change significantly for this number of cycles, which means that the dynamics of the structure to which such system is attached should be essentially constant too.

The results of the material without precipitates are unexpected and very interesting, as plastic deformation is expected to occur during or immediately after the formation of the 6R phase. In order to highlight the effect that precipitates have in the mechanical cycles, cycle number 1000 with and without precipitates is plotted in figure 6.

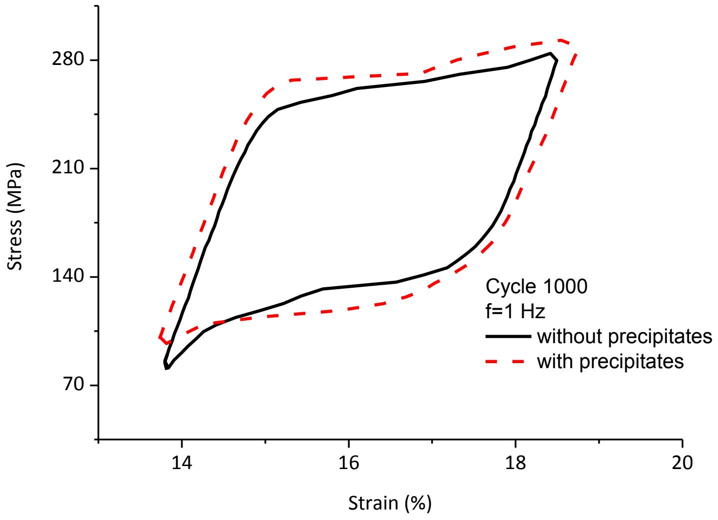

Figure 6. Cycle number 1000, with and without precipitates.

The sample with precipitates has higher transformation stress and lower retransformation stress then the sample without precipitates. This is an expected result given that precipitates function as a mechanical barrier to the propagation of the martensitic transformation/retransformation front. Consequently, the driving force needed for the transition increases, which in turn increases the transformation and decreases the retransformation stresses. This is a desired effect as it increases the hysteresis and makes the material absorb more energy in each cycle.

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The retransformation stress slope is more pronounced in the sample without precipitates and, at the end of the retransformation, the stress is lower than in the sample with precipitates. This result suggests that some plastic deformation might be accumulating in the sample without precipitates as the number of cycles increases, causing stresses to drop during the retransformation, but it is not conclusive. Another possible explanation for the retransformation slope observed in the samples without precipitates is the fact that precipitates might interfere with martensite stabilization, making it slower. Consequently, stabilization in samples with precipitates is expected to occur more slowly than in samples without precipitates, which is a desired effect. In either case, even if some plastic deformation is accumulating in the 6R phase, the behavior of the sample without precipitates is very good, making it a potential candidate for engineering applications, if high frequencies are required.

The high frequency tests were repeated with different samples, with and without precipitates. The results obtained in both tests confirm the results presented here.

The most important physical phenomenon at work here is dynamic stabilization of the 6R martensite. The kinetics of 6R dynamic stabilization and its comparison with 6R stabilization under static conditions has been presented in a previous work [12], which found out that 6R stabilization during mechanical cycling happens much faster than static stabilization, considering the time the material spends in 6R. However, for a given number of cycles, higher frequencies result in less stabilization. This is very interesting because, for most engineering damping applications, frequencies are expected to be approximately equal to or higher than 1 Hz.

The new Fe-base SMAs presented by Tanaka et al [4] and Omori et al [5] have huge pseudoelasticity and hysteresis, making them very interesting candidates for damping devices. However, more data on the dynamic behavior of this alloy is needed before conclusions are drawn regarding its suitability as damping devices.

4 CONCLUSION

The 18R-6R martensitic transition in adequately oriented CuZnAl single crystals SMAs can be potentially used in damping systems that operate for a small number of cycles, especially at frequencies close to 1 Hz. The presence of nanoprecipitates increases the hysteresis of the 18R-6R cycle, thus increasing the damping capacity of the SMA. However, even without precipitates, the material is an effective damper.

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