Stress overshoot in stress-strain curves of $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ metallic glass

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The essential features of the stress overshoot in the stress-strain curves of $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ (at. %) metallic glass that has a wide supercooled liquid region were revealed. The stress overshoot was dependent on temperature, strain rate, and stress relaxation. During the stretch, a change in strain rate gave rise to stress overshoot or undershoot which was sensitive to the variable quantities in the strain rate. © *1997 American Institute of Physics.* [S0003-6951(97)00132-0]

The application of metallic glasses as structural materials has been limited due to limitations of product dimensions and their lack of workability. In order to overcome these shortcomings it is necessary to improve our understanding of the mechanical properties. Although mechanical properties of metallic glasses have been intensively investigated, little attention has been given to the stress overshoot which is a transient stress-strain phenomenon in the homogeneous deformation mode.[1–7] The stress overshoot cannot be explained by a change in sample shape, such as necking, because the phenomenon is also observed under compressive loading.[8,9] The dislocation theory, which explains the yielding phenomenon in crystalline materials, is inapplicable to the glassy alloys. We must look carefully into the stress overshoot for further understanding of the mechanical properties. In this letter, we report on the features of stress overshoot in the stress-strain curves of $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ (at. %) metallic glass that has a wide supercooled liquid region of 105 K that was previously found to exhibit such a stress feature.[1,2]

A $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ glassy alloy ribbon with a cross section of about $1.0\times0.02\ mm^2$ was produced by a single-roller melt-spinning method. The formation of a single glassy phase was confirmed by x-ray diffractometry and transmission electron microscopy (TEM). Thermal properties were measured by differential scanning calorimetry (DSC). The tensile tests were conducted using an Instron-type tensile test apparatus. The test specimens were produced by gluing metallic glass ribbons on the ceramic holders with a ceramic cement. The gauge length was 10 mm. A thermocouple was placed close to the sample and the test was started after holding the specimen at the testing temperature for 200 s.

The glass transition temperature (T_g), crystallization temperature (T_x), and the temperature of the supercooled liquid region ($\Delta T_x = T_x - T_g$) of the $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ glassy alloy are 652, 757, and 105 K, respectively, measured at a continuous heating rate of 0.67 K/s.[10] We conducted the tests in the range of 573–653 K where the stress overshoot appears at strain rates of higher than $5\times10^{-4}\ s^{-1}$.[1] The glassy phase is stable for about 20 ks at T_g.[10] This provides the time window for the testing at these temperatures. We have observed that the stress relaxation after yielding is more pronounced compared with that before yielding.[11] In this study, the starting strain (ϵ_0) for the stress-relaxation experiments was chosen to a strain of 10% from the yield point (ϵ_y). At that strain, the metallic glass is within a steady flow state.

To begin with we would like to report the stress-relaxation dependence of the stress overshoot. Figure 1 shows the stress-relaxation curves at 573, 613, and 653 K. The samples were first stretched at a constant strain rate of $5.0\times10^{-4}\ s^{-1}$ and then held at a strain of 10% from the yield point. The stress values during the relaxation were normalized with the stresses (σ_0) at the time when the cross head was stopped. As Fig. 1 shows, the stress relaxation progressed at higher temperatures. The relaxation time, which is usually represented by the duration required to decrease the stress to one neper, i.e., σ_0/e, was 12, 104, and 303 s at 653, 613, and 573 K, respectively. The saturated stress (σ_e), moreover, decreased with increasing temperature. Here, we defined the difference between σ_0 and σ_e as a stress relaxation of 100%. Figure 2 shows stress-strain curves where the samples were repeatedly relaxed to 0% and

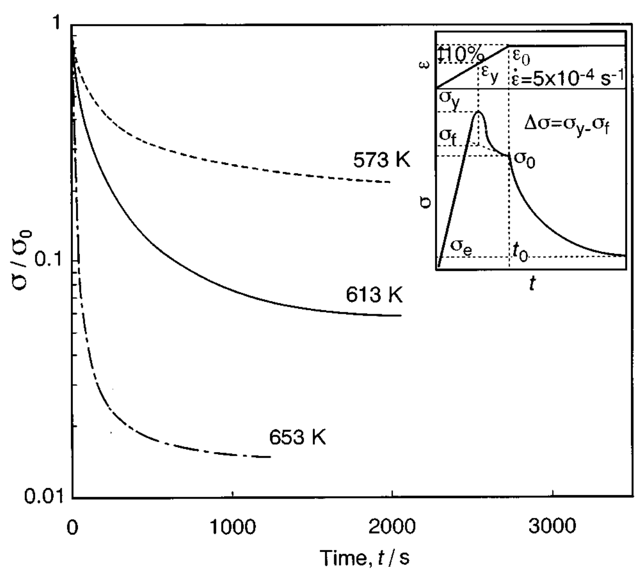

FIG. 1. Stress-relaxation curves at temperatures of 573, 613, and 653 K at a constant strain of 10% from the yield point for a $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ metallic glass ribbon. The stress-relaxation cycle is represented schematically in the inset.

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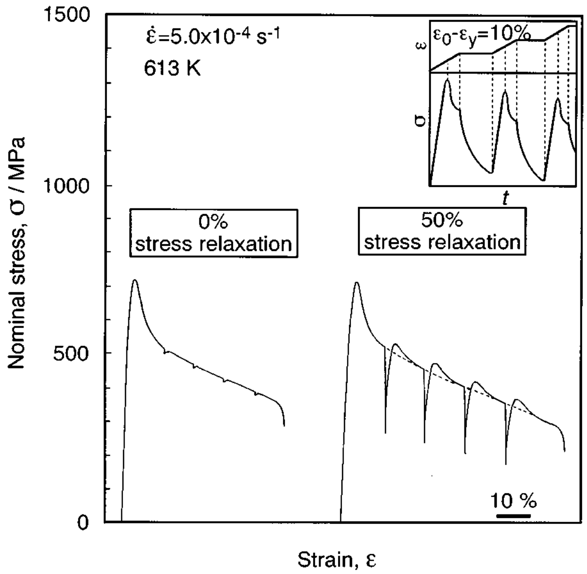

FIG. 2. Tensile stress-strain curves at a temperature of 613 K and at a strain rate of 5.0×10^{-4} s^{-1} for a $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ metallic glass ribbon. The stress was repeatedly relaxed by 0% and 50%, respectively. The tensile and relaxation cycle is represented schematically in the inset.

50% by halting the cross head for appropriate times during the tensile test at a constant strain rate of 5.0×10^{-4} s^{-1}. The tensile and stress-relaxation cycles are shown in the inset. The momentary halt of the cross head, i.e., stress relaxation of approximately 0% resulted in no stress overshoot and no change in the stress-strain curve. On the other hand, the stress overshoot appeared once again after stress relaxation. However, the flow stress remained unchanged by the stress relaxation. The stress overshoot was found to be independent of the number of relaxations throughout all of the experiments. Figure 3 shows the stress-relaxation fraction dependence of the stress overshoot. The stress overshoot increased with the increasing stress-relaxation fraction and decreasing temperature.

Next, we shall discuss the effects of strain-rate change in the course of tensile tests on stress overshoot. Figure 4 shows stress-strain curves at 613 K on quick changes in strain rate.

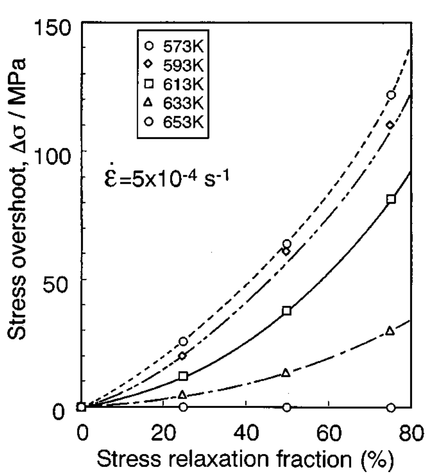

FIG. 3. Changes in the stress overshoot of a $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ metallic glass ribbon after stress relaxation as a function of the stress-relaxation fraction for the tensile tests at a strain rate of 5.0×10^{-4} s^{-1} at various temperatures.

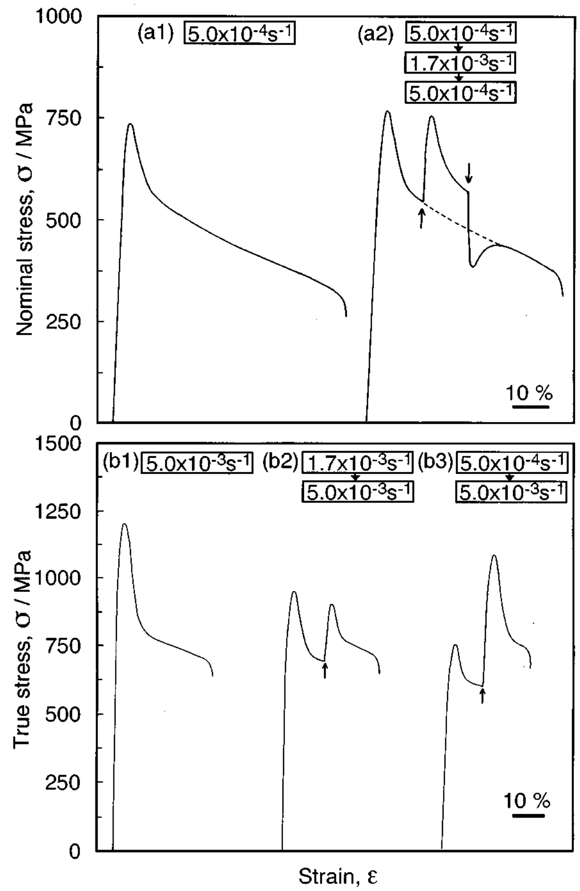

FIG. 4. Stress-strain curves of a $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ metallic glass ribbon at a temperature of 613 K in constant strain-rate tests (a1), (b1) and in strain-rate jump tests (a2), (b2), (b3). The stresses in (a1) and (a2) are shown with nominal stress, and the stresses in (b1), (b2), and (b3) are adjusted by considering the reduction of the cross-sectional area inherent in tensile tests.

Figure 4 (a2) presents a stress-strain curve where the strain rate increased quickly from 5.0×10^{-4} to 1.7×10^{-3} s^{-1} and then decreased quickly back to 5.0×10^{-4} s^{-1}. The stress-strain curve at a constant strain rate of 5.0×10^{-4} s^{-1} is shown in Fig. 4 (a1) for comparison. Although there was no stress relaxation, the stress overshoot appeared quickly after increasing the strain rate. It can be seen that the quick decrease in the strain rate resulted in a stress undershoot and that the steady flow stress at each strain rate remained unchanged. Figure 4 (b1) shows the stress-strain curve at a constant strain rate of 5.0×10^{-3} s^{-1}. The yield stress (σ_y) and stress overshoot ($\Delta\sigma$) were 1190 and 380 MPa, respectively. The stress overshoot was 32% of the yield stress. Figure 4 (b2) shows the stress-strain curve when the strain rate was increased quickly from 1.7×10^{-3} to 5.0×10^{-3} s^{-1}. The stress overshoot after changing the strain rate to 5.0×10^{-3} s^{-1}, however, was only 105 MPa, resulting in a yield stress of 895 MPa which was much smaller than 1190 MPa at a constant strain rate of 5.0×10^{-3} s^{-1}. This method led accordingly to a large drop in the maximum yield stress from 1190 to 945 MPa, namely, a 21% reduction. On the other hand, a large increase from 5.0×10^{-4} to 5.0×10^{-3} s^{-1} led to a larger stress overshoot of 280 MPa, as shown in Fig. 4 (b3). This value was 100 MPa smaller than that at a constant strain rate of 5.0×10^{-3} s^{-1}. These results show that a small increment in the strain-rate change leads to a lower stress overshoot, resulting in lower stress. This method seems to be especially more effective at higher strain rates or lower temperatures where the stress overshoot becomes larger.[1] Thus, it is clear that the stress overshoot or undershoot appears on a quick increase or decrease in strain rate, respectively, and is also dependent on the increment of strain rate increase or decrease.

To summarize, we have revealed the stress overshoot behavior in the stress-strain curves of $Zr_{65}Al_{10}Ni_{10}Cu_{15}$ metallic glass that has a wide supercooled liquid region. The stress overshoot depended on the stress-relaxation fraction, temperature, and strain rate. Moreover, a stress overshoot or undershoot was observed on a quick increase or decrease in the strain rate during the stretch, respectively. The stress overshoot was also found to be sensitive to the increment in the strain-rate change. These phenomena also seem to be observed for compression. These features of the stress overshoot and undershoot can be explained by viscoelasticity and they seem to be applicable in principle to other metallic glasses with and without a supercooled liquid region.

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