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EFFECT OF DEFORMATION AND PRESTRAIN MODE ON THE FLOW BEHAVIOR OF Ti-6Al-4V (PREPRINT)

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14. ABSTRACT
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Effect of Deformation and Prestrain Mode on the Flow Behavior of Ti-6Al-4V

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Abstract

The effect of strain path on the plastic-flow behavior of Ti-6Al-4V with a colony-alpha perform microstructure was determined. Specifically, the stress-strain response in compression following a prestrain via torsion, compression, or rolling was interpreted. It was found that the flow-softening parameter γ_f was dependent on the level of the prestrain, but independent of the mode of prestrain. After a prestrain of ~0.3, however, γ_f decreased very slowly.

Keywords: stress-strain, flow softening, strain-path effects

1. Introduction

Bulk hot working of alpha/beta titanium alloys such as Ti-6Al-4V is used to convert coarse beta-grain ingot structures with lamellar (colony) alpha into billets with a fine, equiaxed (globular)-alpha microstructure. One of the most important steps in the conversion process consists of the breakdown of the lamellar colony or acicular microstructure formed during cooling after beta working or recrystallization heat treatment. This breakdown operation usually comprises upsetting or cogging followed by annealing in the alpha/beta phase field to produce a globular-alpha structure. Despite the apparent simplicity of the processes employed, undesirable defects in finished wrought products may develop. These defects include gross fracture, shear bands, and internal cavities [1-4].

In view of the engineering importance of titanium alloys, a significant amount of research has been devoted to understand plastic flow and microstructure evolution during the various stages of primary (mill) processing with particular emphasis on the behavior during hot working in the alpha/beta field. In this regard, a number of laboratory-scale test techniques have been utilized. These methods include uniaxial tension, uniaxial compression, simple shear (e.g., torsion, equal-channel, angular extrusion), and small-scale forging, among others [2, 5-7]. In order to obtain a better understanding of complex industrial processes, tests that combine different stress modes and strain-path changes have also been employed. The results from such simulative tests have been interpreted using both phenomenological and mechanistic approaches [8-10].

The objective of the present work was to compare and interpret the flow behavior of a typical alpha/beta titanium alloy (Ti-6Al-4V) with a colony-alpha microstructure deformed under various monotonic and strain-path-change conditions. By this means, the influence of the mode of prestraining on subsequent flow behavior was delineated.

2. Material and procedures

The present work comprised an analysis of flow stress data from a number of previous investigations as well as some new results. In all cases, the material used was Ti-6Al-4V. As described in References 5 and 11, the material had been heat treated to produce a colony-alpha microstructure with a prior-beta grain size (and comparable colony size) of ~100 μm and a grain-boundary-alpha layer approximately 2-3 μm thick (Figure 1).

The experimental details of previous flow-stress tests based on torsion, reversed torsion, torsion-compression, and rolling-compression can be found in References 5, 11 - 13. Compression-compression tests from unpublished research [14] consisted of a compression step using specimens measuring 17.8-mm diameter and 30.5-mm height. After compression and gas cooling to room temperature, a second cylindrical sample was machined from each of the deformed samples using wire EDM. The compression axis of these so-called second-generation samples was parallel to the radial direction of the initial samples. To remove the recast layer produced by EDM, the specimens were machined to final dimensions of 7.6-mm diameter and 11.4-mm height. Similar to the work reported previously [5, 11-13], all of the compression-compression tests were conducted under constant-strain-rate isothermal conditions; heating was accomplished using a controlled-atmosphere radiant furnace.

3. Results and discussion

The principal results from this work comprised analysis of the flow behavior during monotonic torsion, reversed torsion, torsion followed by compression, and sequential compression along two orthogonal directions of Ti-6Al-4V with a colony-alpha starting microstructure.

3.1. Monotonic torsion

Effective stress - strain curves for monotonic torsion at surface effective strain rates of 0.04 or 0.69 s^{-1} and a temperature of 815°C are summarized in Figure 2. These curves revealed marked flow softening at hot-working temperatures. The softening occurred continuously throughout the entire deformation; however, its rate decreased with strain. Previous work [10] attributed this softening to the loss of the alpha-beta interface strength. In the present work, the softening magnitude was quantified for four successive strain intervals of ~0.50 using the relationship $\gamma_f = (\sigma_s - \sigma_f)/\sigma_s$, in which σ_s and σ_f denote the stress at the beginning and end of the interval, respectively. As shown in Figure 2, the flow softening parameter decreased from 0.22 for the strain interval between 0 and 0.5 to 0.08 for the 1.5-to-2.0 strain interval. The strain-rate-sensitivity index was estimated to be ~0.15 using the peak stresses for the flow curves at the two different strain rates; this value is in agreement with measurements for Ti-6Al-4V tested in compression under similar conditions [2].

3.2. Two-step torsion tests with or without reheating

Flow curves for three torsion tests during which the twisting direction was or was not reversed after a "forward" deformation of 125 deg. (surface effective strain of 0.99) are shown in Figure 3. In one test, the strain direction was reversed quickly; the ''dwell'' time for the change of twisting direction was 1 - 2 s. In a second test, the specimen was water quenched after the forward twist, reheated and soaked at the initial test temperature for 10 min, and then twisted in the reverse direction. The third test was identical to the second one, except that the strain direction was not reversed; i.e., the sample was water quenched after the forward twist, reheated, soaked for 10 min, and then strained again in the forward direction. For the two experiments comprising a forward and a reverse deformation, there was a noticeable difference in the flow behavior during the reverse twist (Figure 3). Specifically, after reversing the strain path, the test without the reheating sequence exhibited strain hardening until a peak stress was achieved at a strain increment of ~0.20 from the beginning of the reversed loading, and subsequent flow softening was limited. For the test in which the sample was water quenched and then reheated, the flow curve for the reverse twist resembled that of the forward deformation, i.e., a peak stress followed by flow softening. The flow curves for the two tests including the reheat were similar (Figure 3). However, the flow-softening parameter was somewhat higher when the strain direction was not changed. In particular, for the experiment in which the straining direction was not reversed after the reheat, the flow-softening parameter was comparable to that observed in during compression following torsion, discussed below in Section 3.3.

The explanation for the different reloading transients in the two-step torsion tests lies in the nature of the microscopic slip process. Specifically, the initial flow softening (at low strains) is due to slip transfer across the alpha-beta interfaces. When the deformation is rapidly reversed (without cool-down and reheating of the specimen) there may be a large number of mobile dislocations that can move easily in the reverse direction giving rise to lower initial stresses during reloading. Because the original alpha-beta interfaces have now been broached, it may be easier to form subgrain-like substructures in both the alpha and beta phases, thus leading to a strain-hardening regime and then near steady-state flow as in single-phase materials whose flow is controlled dynamic recovery [15, 16]. On the other hand, the reverse step of the "interrupted" test showed a behavior which resembles that of the forward-torsion stage, i.e., a peak stress was achieved after a strain of only 0.06 and flow softening occurred, albeit at a lower rate (γ_f = 0.09 for the strain interval of 0 – 0.5 during reversed torsion) than during forward torsion. For the "reheat" test that did not involve a change of the straining direction, the peak stress was also achieved after a low strain of ~0.06; however, the flow-softening parameter was similar to that for the forward step; i.e., γ_f = 0.19 for the strain interval of 0 – 0.5. The observations for the two tests including reheating can be rationalized on the basis of a partial restoration of the character of alpha-beta interfaces (associated with motion of the interface as the phase volume fraction changed) and changes in the nature of the dislocation substructure during heating and soaking prior to the initiation of the second torsional step, albeit in the forward or reverse direction.

3.3. Torsion-compression

The flow behavior of Ti-6Al-4V during combined torsion-compression testing is shown in Figure 4. In particular, the data are summarized for compression tests conducted on samples extracted from the *shoulder* of torsion specimens (for which the prestrain was zero) or the gage length of torsion samples which had been twisted by 125° or 225°, yielding an effective prestrain *at the surface* of 0.99 or 1.78, respectively. For comparison purposes, the flow curve for reversed torsion (with cool-down/reheating) from Figure 3 is also plotted in Figure 4. The key observations from this figure are the following: (i) the material exhibited a higher softening rate in compression as opposed to torsion, irrespective of the magnitude of imposed prestrain and (ii) both the peak stress and the flow softening rate were reduced by prestraining; however, the magnitude of the decrease for both quantities was reduced with increasing prestrain.

The flow-softening parameter γ_f in torsion and compression was quantified with the relationship from Section 3.1. Due to the smaller strain imposed during compression (effective strain ~ 0.29), γ_f was calculated for $\bar{\varepsilon}$ = 0.25, i.e., $\gamma_f = (\sigma_p - \sigma_{\bar{\varepsilon}=0.25}) / \sigma_p$. For compression, this ratio was equal to 0.26, 0.12, and 0.09 for torsional prestrains corresponding to *surface* effective strains of 0, 0.99, and 1.78, respectively. By contrast, the values of γ_f for reversed torsion (using interrupted testing) (Figure 3) were equal to 0.14 and 0.03 for torsional prestrains of 0 and 0.99, respectively.

In a similar vein, Miller, et al. [17] observed different apparent flow-softening behaviors for Ti-6Al-4V with a colony-alpha microstructure deformed in tension and compression at a temperature of 815°C and a strain rate of 0.1 s^{-1}. Specifically, it was found that the rate of flow softening in tension was greater than in compression. These differences in flow behavior with respect to the mode of deformation, however, were partially ascribed to variations of texture hardening during deformation. Such an effect was quantified by Semiatin and Bieler [18], who reported the compression behavior for samples extracted from various directions of a textured plate. From these tests, the discrete contributions of texture hardening and microstructure changes per se on flow-softening behavior were deduced. By this means, it was concluded that the contribution of microstructure changes to flow softening does not change significantly with test direction.

3.4. Compression-compression tests

The shapes of the flow curves for compression-compression tests [14] (Figure 5) were similar to those torsion-(interrupted) torsion. That is to say, significant flow softening was observed during the initial compression, and the peak stress for the second (orthogonal) step was lower and was reached at a low strain (less than 0.05). In addition, the compression-compression tests indicated that the initial colony/beta grain size did not influence the flow behavior for these testing conditions. For the two beta sizes used (100 μm and 500 μm), the flow curves were essentially identical.

3.5. Influence of prestrain mode on compression flow behavior

The effect of the mode of prestraining (i.e., rolling, compression, torsion) on subsequent behavior in compression of Ti-6Al-4V with a colony-alpha microstructure was also quantified by an analysis of existing flow stress data (references 13, 14**,** and 12 for prestraining via rolling, compression, and torsion, respectively). Figure 6 illustrates the orientation of the compression tests in each case.

Initially, the similarity of the starting materials was assessed by comparing values of the peak stress from compression flow curves for the unstrained material in each case (Figure 7). Because different strain rates were used during prestraining, the measured values of peak stress were adjusted to 0.04 s^{-1} using a strain rate-sensitivity exponent m = 0.15. The peak stresses at 815°C were essentially the same in all cases, thus providing credibility in comparing the flow behavior *following* prestraining. Similarly, the peak stresses at 900°C were also found to be essentially the same.

Secondly, the flow-softening parameters (γ_f) for the compression behavior following prestraining were determined and compared. Because of the limitations associated with torsion-compression, γ_f for all prestrain modes was based on the peak stress and the stress at a strain interval of 0.25 during the *reloading* compression tests for two different temperatures, i.e., 815°C and 900°C. The dependence of γ_f so determined as a function of effective prestrain is given in Figures 8a and b. For the specific instance of pre-deformation in torsion for which the strain varies from zero at the center of the specimen to the maximum strain at the surface, the prestrain was taken to be the *average* strain imposed on the specimen, i.e., the strain at the mid-radius. The results indicated that the flow-softening parameter determined in this manner is independent of the prestrain mode, inasmuch as all of the data fall on the same trend line. In addition, Figures 8a and b show that the flow-softening parameter experiences a sharp decrease at low prestrains, while it decays slowly after a prestrain of ~0.3.

4. Summary

The plastic-flow behavior of Ti-6Al-4V with a colony-alpha microstructure determined by different test techniques was summarized and compared. These techniques included monotonic torsion and compression as well as combined torsion-torsion, torsion-compression, compression-compression, and rolling-compression. Special attention was focused on the magnitude of the flow-softening parameter γ_f after pre-deformation by torsion, compression, or rolling to various strain levels. When the magnitude of the pre-deformation in torsion is associated with that at the mid-radius, it was found that γ_f was dependent only on the level of the prestrain; i.e., the prestrain mode does not affect the flow behavior during the subsequent hot working step. However, the parameter decreases at a low rate after a prestrain of ~0.3.

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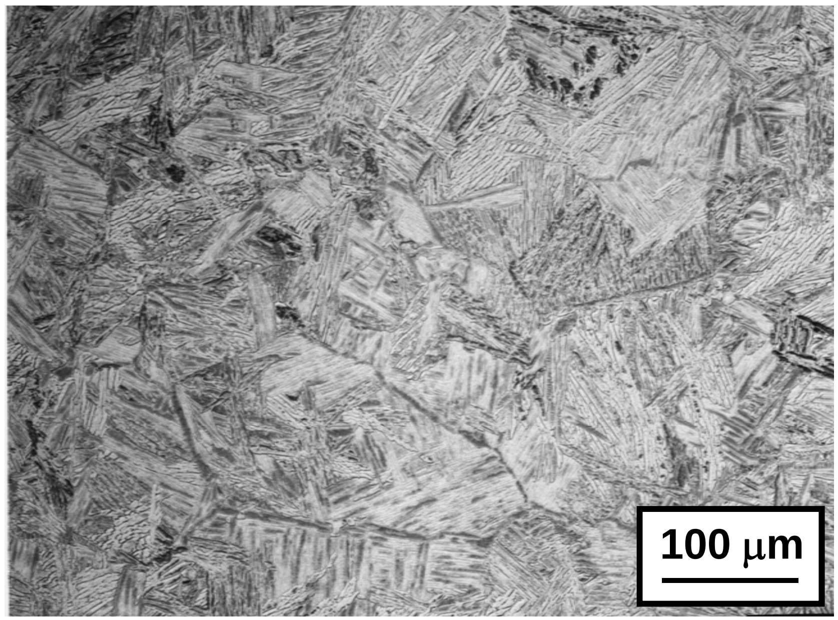


Figure 1. Micrograph of Ti–6Al–4V with a colony-alpha microstructure.

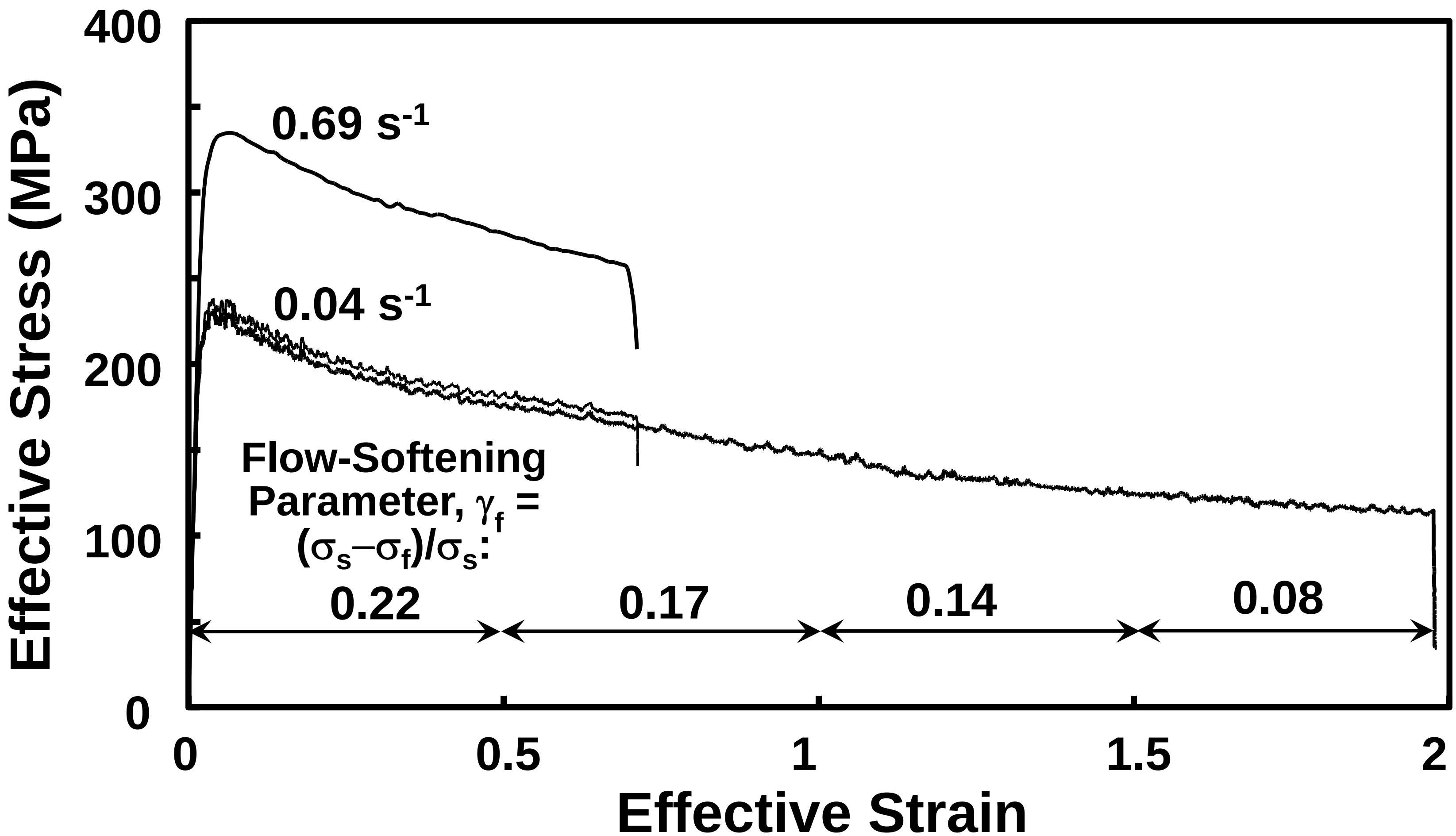


Figure 2. Effective stress-strain curves for monotonic torsion at 815°C and two different surface effective strain rates. The flow-softening parameter γ_f for several strain intervals is also shown on the plot.

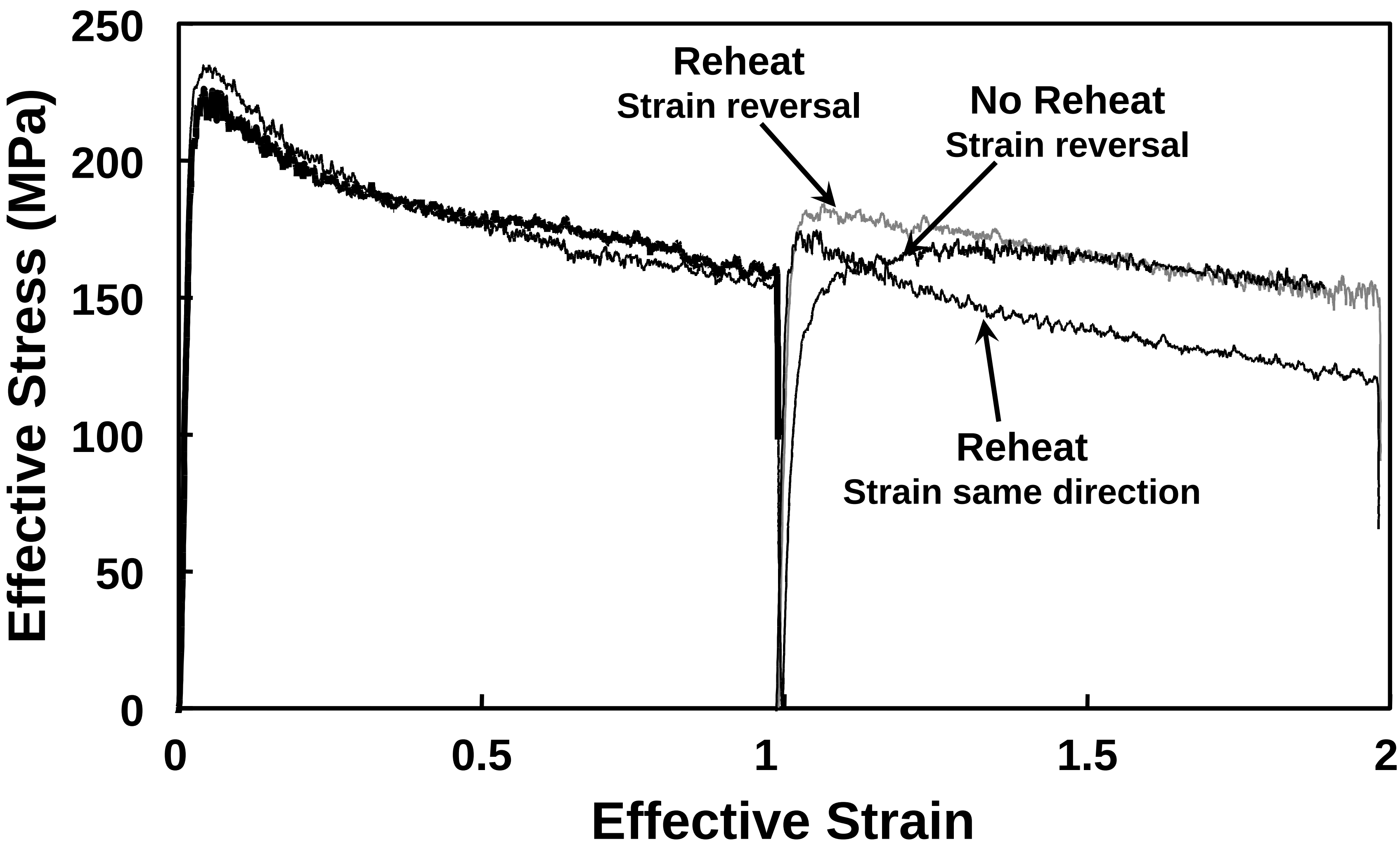


Figure 3. Effective stress-strain curves for reversed-torsion tests at 815°C and a surface effective strain rate of 0.04 s^{-1}. The second torsion step was conducted without or with an intermediate cool-down and reheat. For the reheated samples, the strain was either reversed or remained along the same (initial) twisting direction.

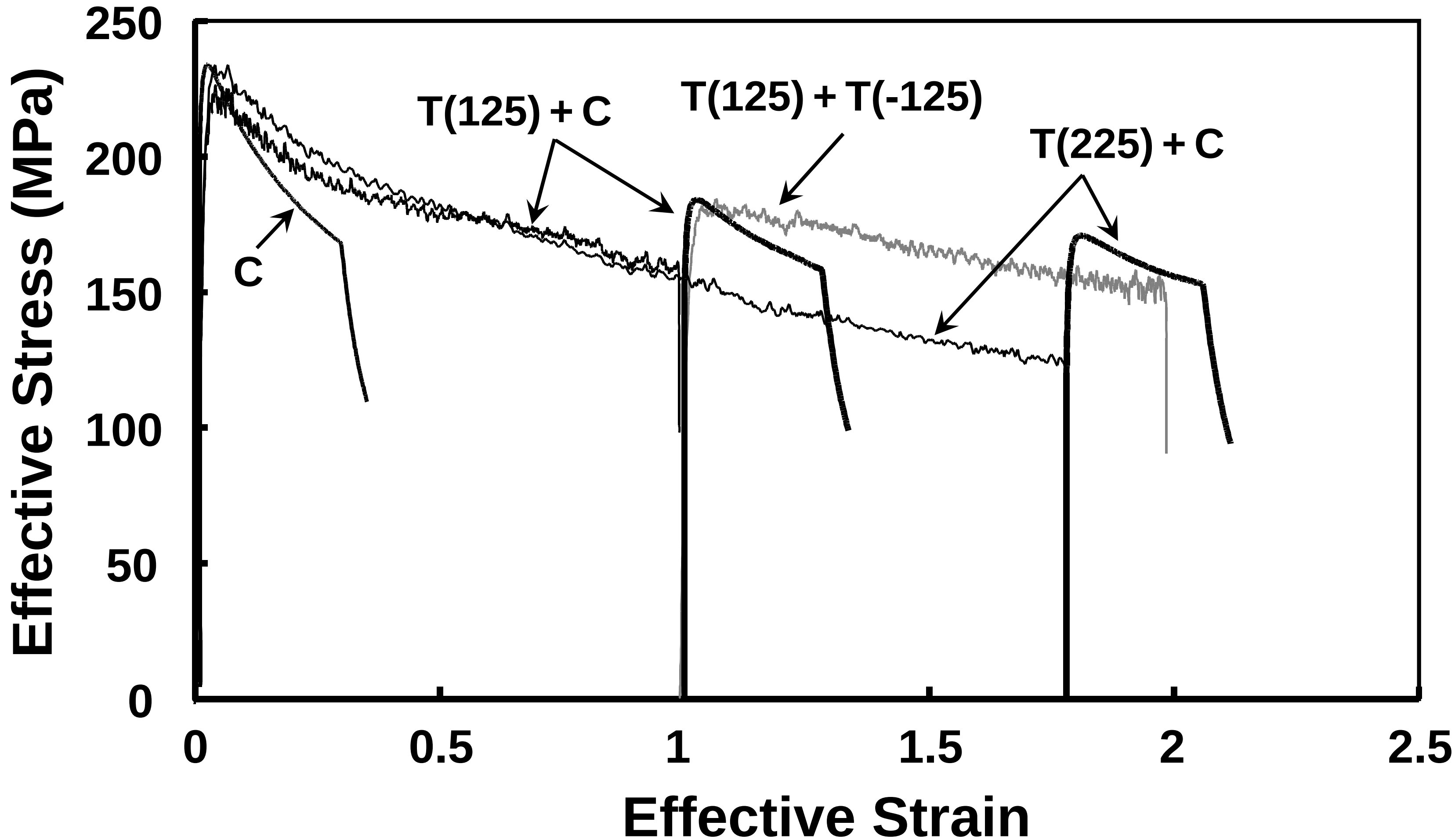


Figure 4. Effective stress-strain curves for torsion-compression tests at 815°C and an effective strain rate of 0.04 s^{-1}. The symbols in the graph denote the loading mode (T for torsion, C for compression); the twist angle in degrees is given in parentheses.

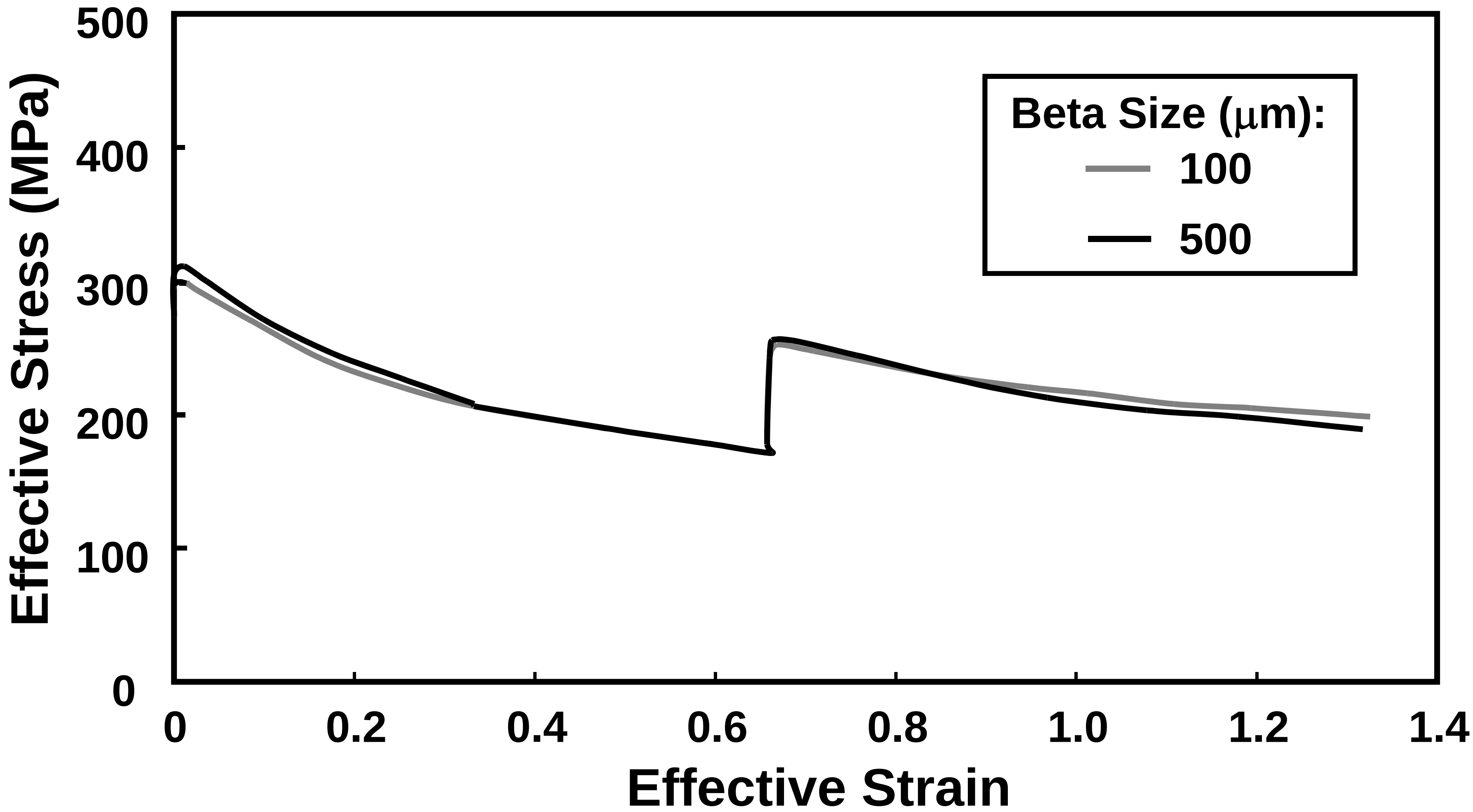


Figure 5. Effective stress-strain curves for compression-compression deformation at 815°C and an effective strain rate of 0.1 s^{-1} on specimens with two different beta grain sizes.

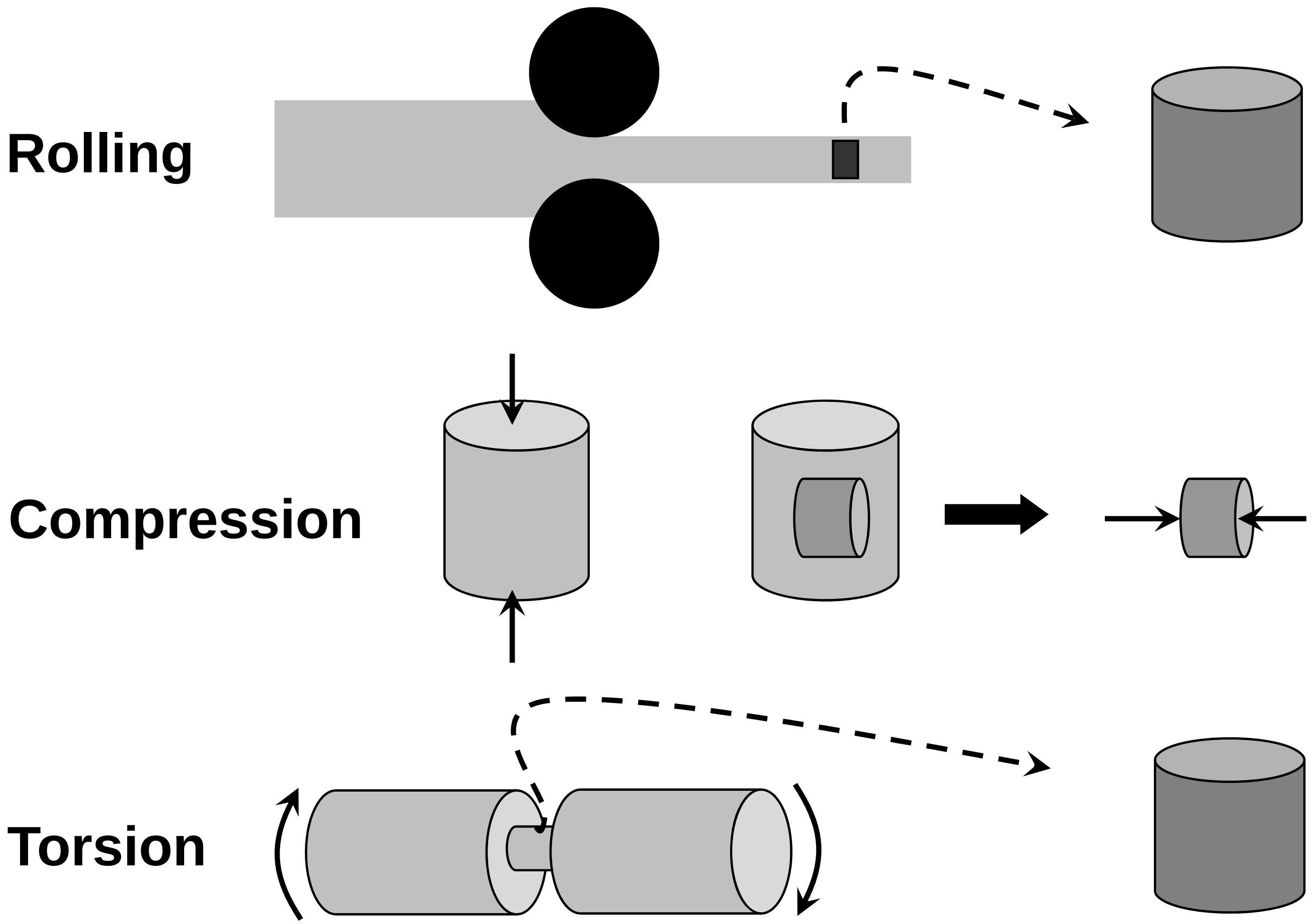


Figure 6. Schematic illustration describing the different prestrain modes for subsequent compression testing.

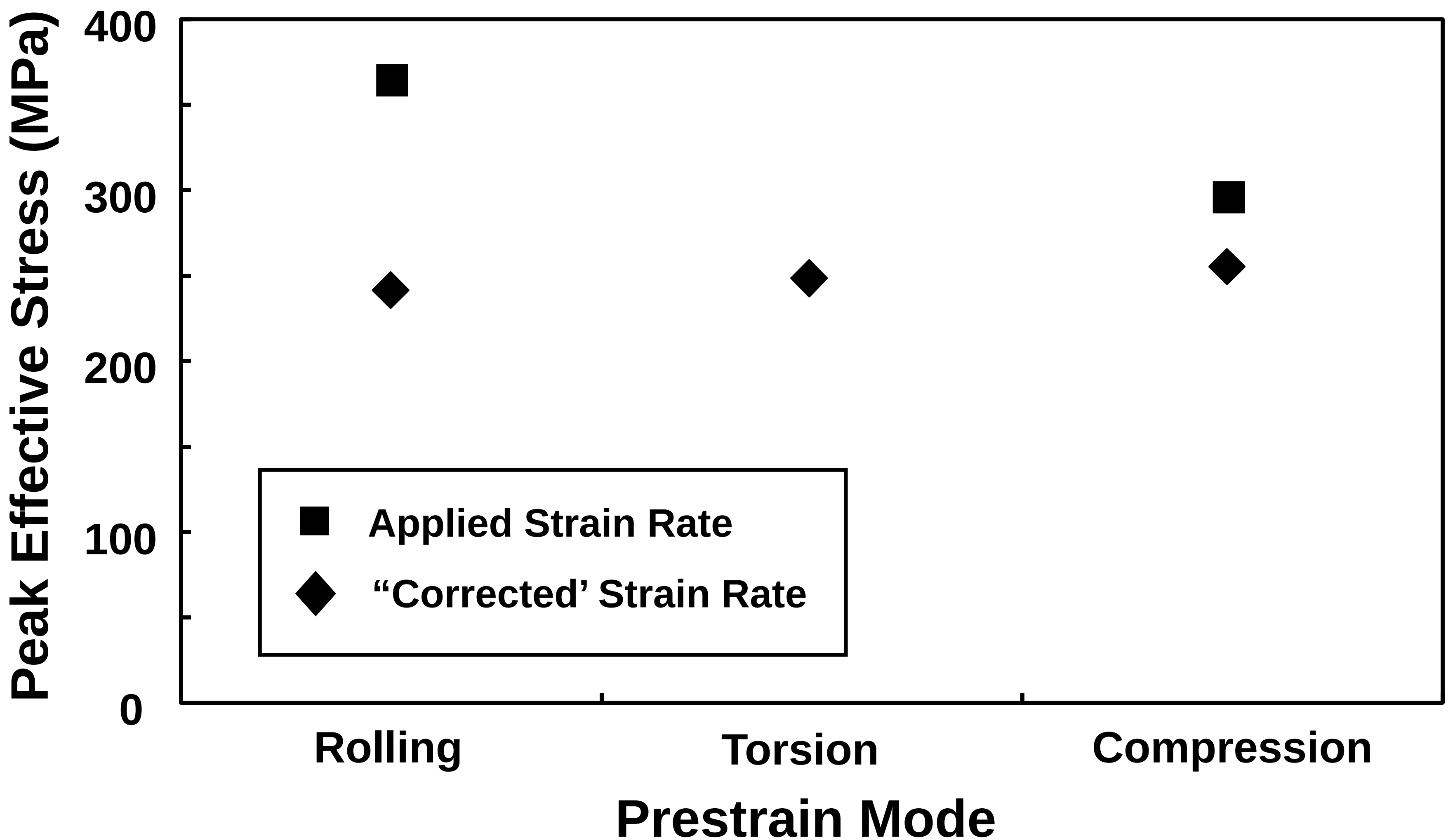


Figure 7. Peak stress during prestraining of Ti-6Al-4V. The data correspond to a temperature of 815°C; all data points were adjusted to a strain rate of 0.04 s^{-1} using a strain-rate sensitivity equal to 0.15.

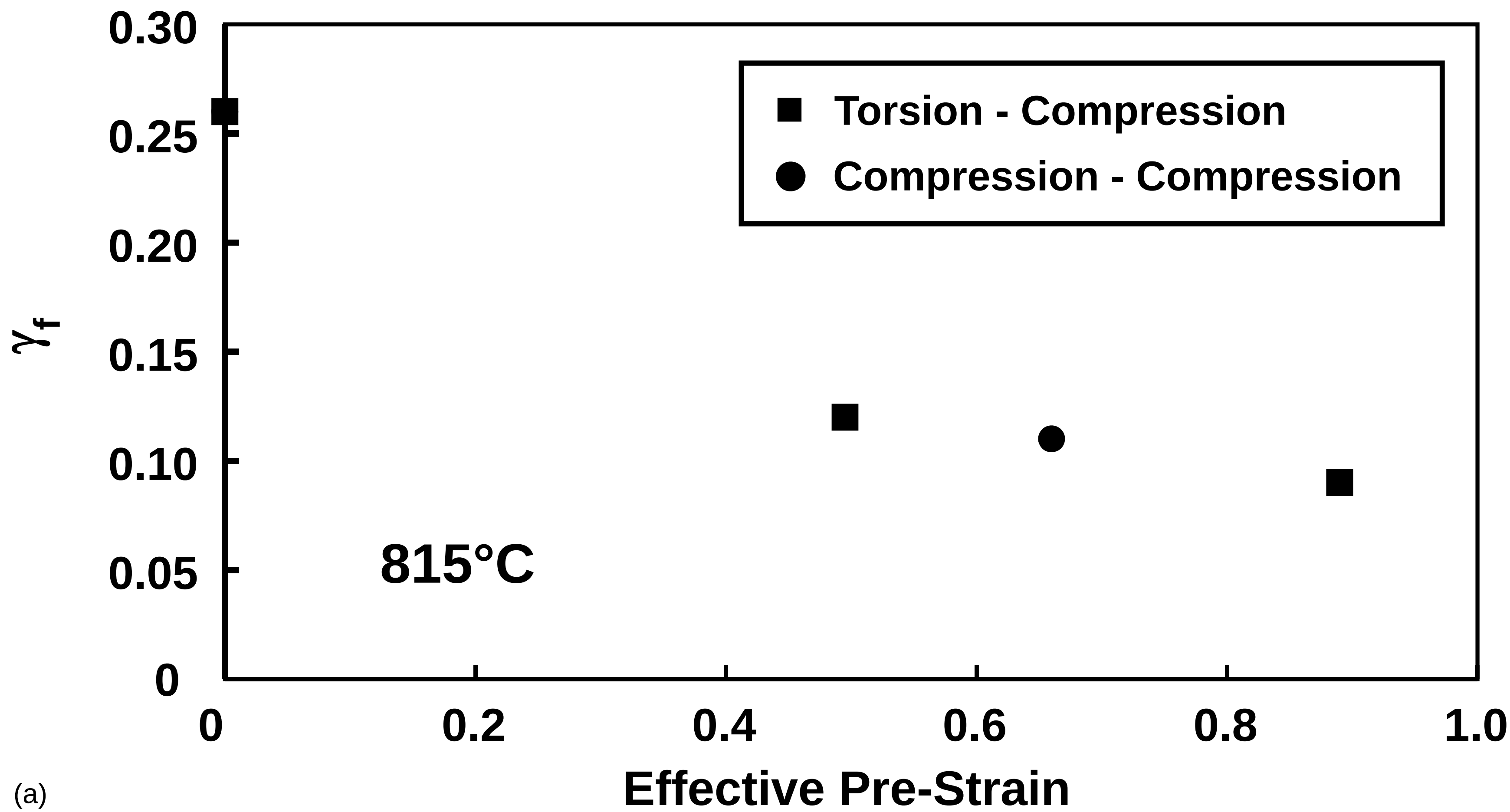
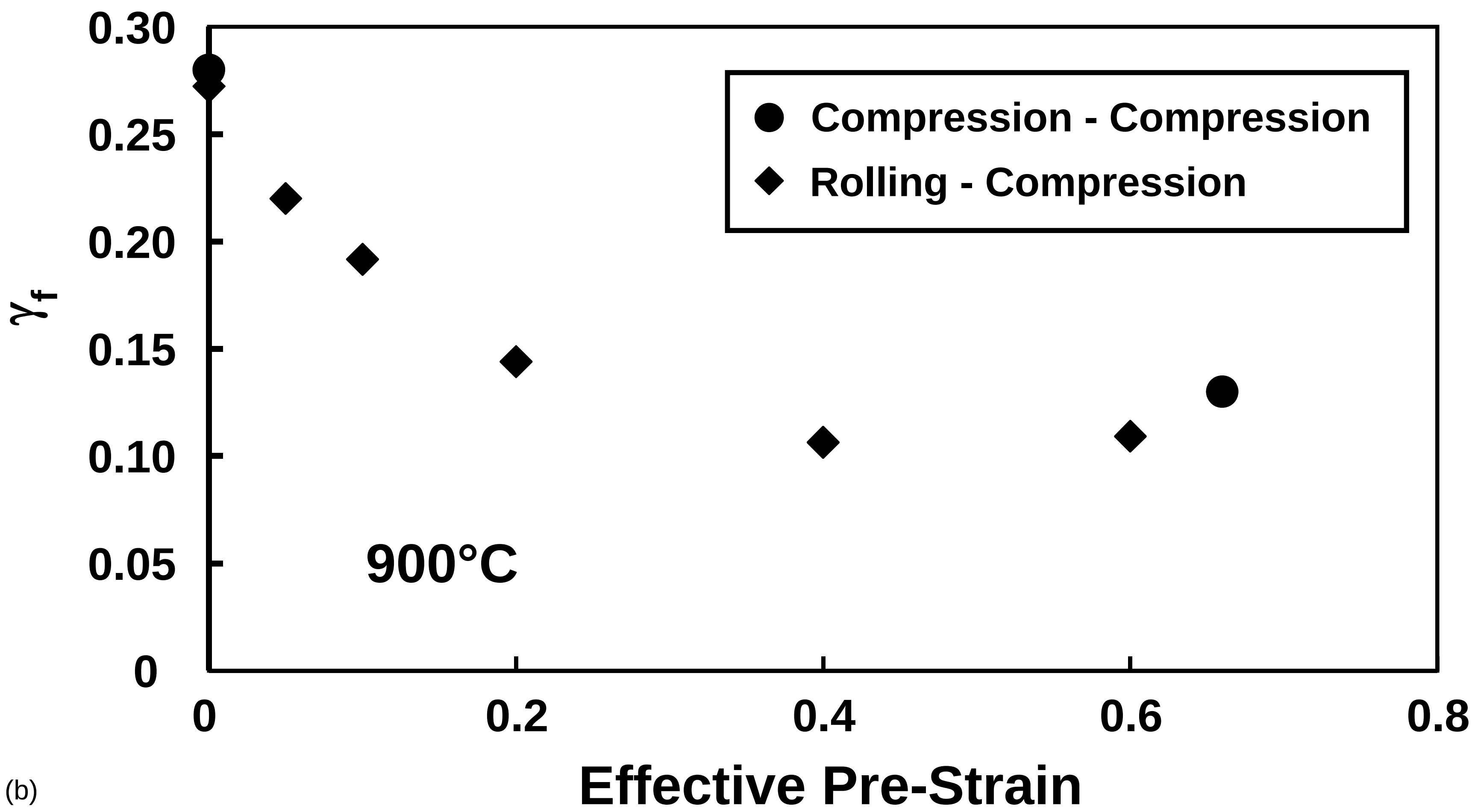


Figure 8. The flow-softening parameter γ_f as a function of prestrain for the different prestrain modes at temperatures of (a) 815°C or (b) 900°C.



(b)

Figure 8. (Continued)