JOURNAL OF APPLIED POLYMER SCIENCE VOL. 16, PP. 2523-2530 (1972)

The Effects of Initial Nonconstant Transient Cross-Head Speed on the Stress-Strain Curve of Viscoelastic Material

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Synopsis

The effects of initial nonconstant transient cross-head speed inherent to every tensile tester, especially in high-speed tension, on the shape of stress-strain curves of viscoelastic materials were studied. In case of brittle polymers, the specimen was subjected to variable strain rates throughout the test loading, although the constant strain-rate tension is planned, since the cross-head speed stays within the initial nonconstant transient range due to its small total elongation until fracture and never reaches the prescribed constant cross-head speed achieved after considerable cross-head travel. As the polymers were quite strain-rate sensitive, it was necessary to employ a device to extend the specimen at constant strain rate, i.e., the constant cross-head speed from the beginning to obtain the stress-strain curve at the exactly prescribed constant strain rate for such brittle polymers. The "slack grip" concept was then introduced and its effectiveness was experimentally verified. In conclusion, the effects of such initial transient cross-head speed are not negligible for brittle polymers and can be avoided by using the "slack grip."

INTRODUCTORY ANALYTICAL SURVEY

In our experience in tensile testing to obtain a stress-strain curve up to several meters per second, it seemed unavoidable that every tensile tester, although designed to keep a constant cross-head speed V, which is related to the strain rate $\dot{\epsilon}$ in terms of $\dot{\epsilon} = V/l_0$, where l_0 = the initial specimen length, inherently tended to have several initial nonconstant transient cross-head speeds, especially in high-speed tension, and usually in two ways, as shown in Figures 1 and 2. In Figure 1, the cross-head speed monotonously approaches the prescribed constant cross-head speed like over damping, while in Figure 2 the cross-head speed first exceeds the prescribed constant cross-head speed and then approaches the prescribed constant cross-head speed like in critical damping. This means that the test specimen is subjected to variable transient cross-head speeds until its elongation

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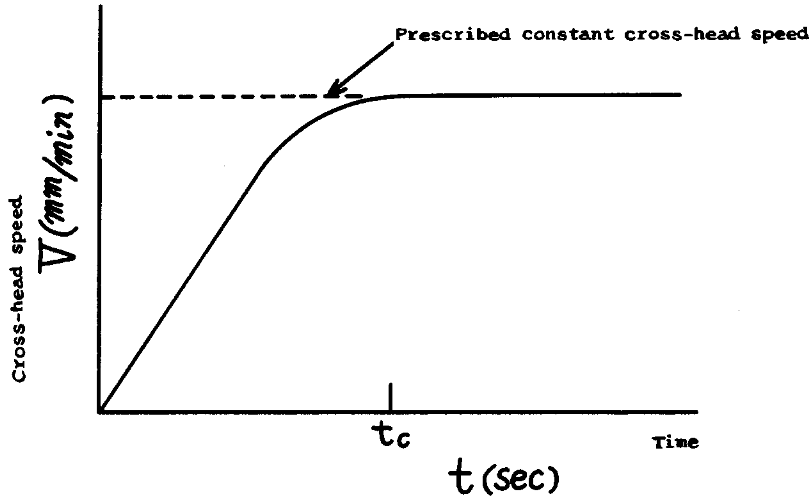

Fig. 1. Cross-head speed vs. time curve (over damping type).

reaches a length equivalent to a cross-head travel realized during time t_c in Figures 1 and 2. In other words, the specimen is partially subjected to a transient cross-head speed other than the prescribed constant cross-head speed, provided $t_f > t_c$, and entirely so, provided $t_f < t_c$, where t_f = the time of fracture. That is, a specimen having a mechanical property of small amounts of deformation until fracture is to be subjected to further different cross-head speed throughout or in part during the extension up to fracture other than the prescribed constant cross-head speed, since the cross head does not have enough travel to attain the constant cross-head speed due to the small total elongation of the specimen.

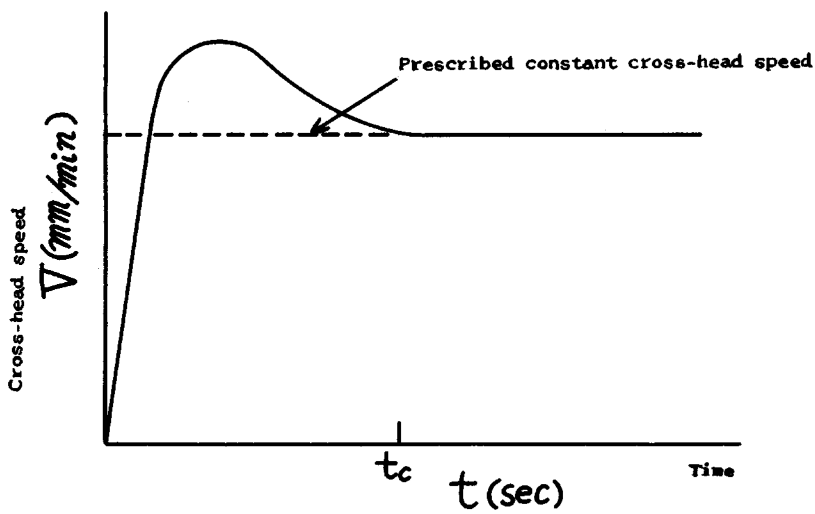

Fig. 2. Cross-head speed vs. time curve (critical damping type).

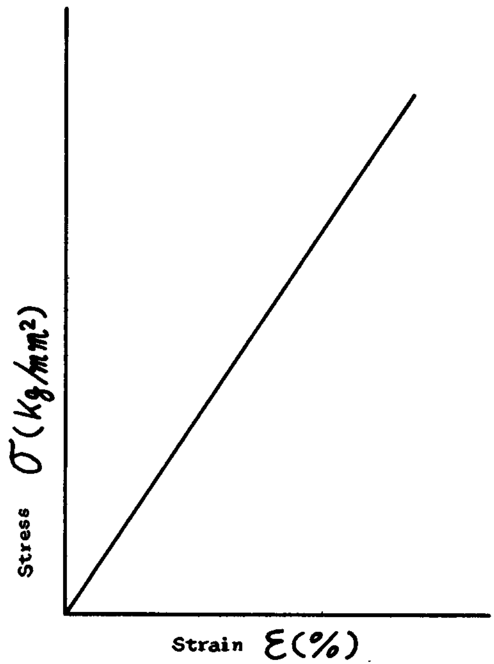

Fig. 3. Stress–strain curve of perfectly elastic material for any strain rate.

As is well known, if the specimen of interest is of perfect elasticity, no cross-head speed effect is introduced on the stress–strain relation, and consequently the shape of stress–strain curve obtained in the tensile test remains unchanged under any cross-head speed, as shown in Figure 3, so that no problem arises in this case, no matter how long the transient cross-head speed range.

However, this is quite a hypothetical and ideal case. In reality, every existing material possesses at least some viscosity, thus making the mechanical property viscoelastic, and the shape of the stress–strain curve is affected more or less by the applied strain rate, i.e., the cross-head speed. The viscosity element is governed by Newton's postulate, and therefore it is strain-rate sensitive. Many experimental facts obtained heretofore support this supposition.

Viscosity is especially predominant in polymers. Therefore, shapes of stress–strain curves up to fracture are sensitive to the applied strain rate, i.e., the cross-head speed, as is easily understood by employing a simple equivalent model, for example, a three-parameter model for linear polymers as shown in Figure 4.[1] However, ductile polymers fortunately show $t_f \gg t_c$, so that their elongation until fracture becomes very large. Consequently, the length of such transient cross-head speed ranges becomes negligible compared with the total elongation until fracture, and the applied cross-head speed can be regarded to be approximately equivalent to the prescribed

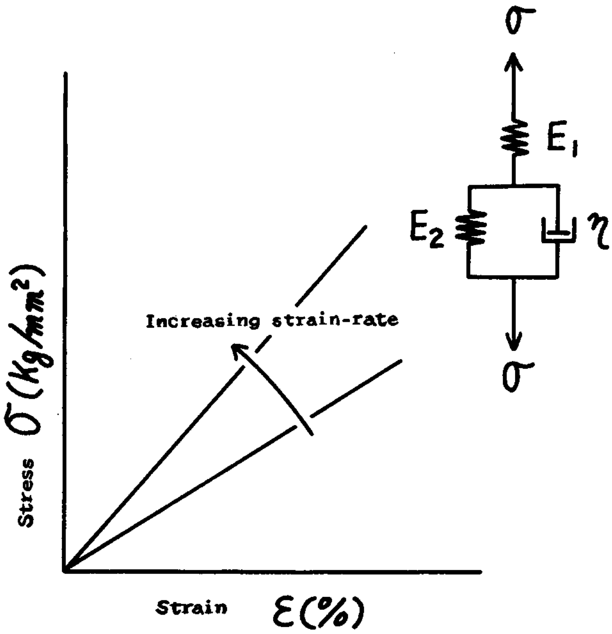

Fig. 4. Stress–strain curve of three-parameter model, showing strain rate dependence.

constant cross-head speed from the beginning. Therefore, the shape of the stress–strain curve obtained up to fracture is little affected by the initial transient cross-head speed.

Brittle polymers exhibit only small elongation until fracture, say, $t_f < t_c$ or $t_f \approx t_c$ at best, and so the realized cross-head speed will be in the transient range. Therefore, the obtained stress–strain relation will be considerably affected by the initial transient cross-head speed, resulting in the wrong stress–strain curve obtained at a variable cross-head speed different from the prescribed, constant cross-head speed. Therefore, the tensile test to obtain the stress–strain curve for brittle polymers subjected to high-speed deformation must especially be done at exactly constant prescribed strain rate or cross-head speed throughout the test loading from the beginning. To achieve this, the authors adopted a "slack grip" concept, details of which were given in an earlier paper.[1]

As discussed above, the effects of transient cross-head speed on the stress–strain curve might be expected to be influential for brittle polymers, especially in high-speed tension, and experimental investigations using such "slack grip" will be described in what follows.

EXPERIMENTAL

Tensile Tester. An IM-100 tensile tester, manufactured by Shimadzu Seisakusho Ltd., Japan, was employed. It has a maximum capacity of 100 kg tension at 1000 mm/min cross-head speed. This tensile tester has a

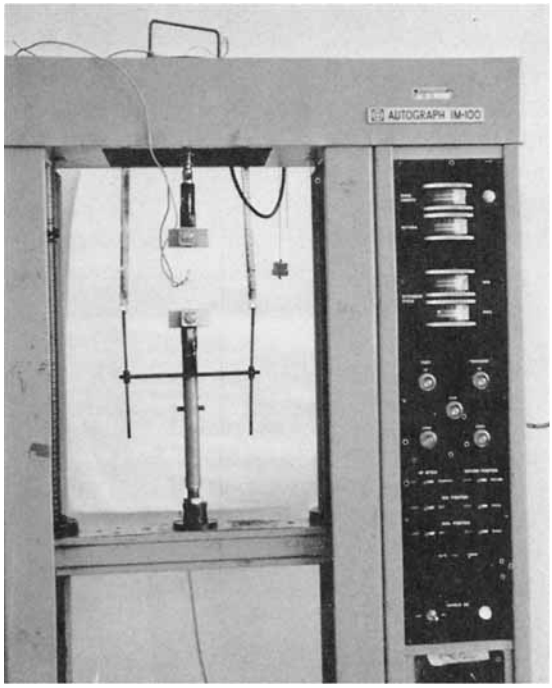

Fig. 5. Setup of IM-100 tensile tester with "slack grip."

transient cross-head speed characteristics of a type shown in Figure 1. Special "slack grip" was used to give a specimen a prescribed constant cross-head speed from the very start of tension loading, details of which were described in the previous report.[1] A setup of the IM-100 tensile tester with the "slack grip" is shown in Figure 5.

Specimen. A poly(methyl methacrylate) specimen measuring 180 mm × 10 mm × 1 mm was prepared from the original virgin Sumipex sheet manufactured by Sumitomo Chemical Co. Ltd., Japan. The distance between jaws for gripping is 100 mm. Six pieces of the specimen each were tested with and without "slack grip."

Measurements. A load cell using a strain gauge was used to measure the applied load during tension, and strain gauges were employed to measure the produced strains. These strain gauges were placed on both surfaces of a specimen to avoid eccentric contribution. All these data were recorded by use of an electromagnetic oscillograph, EMO-1 Photocorder, manufactured by Yokogawa Electric Works Ltd., Japan. Test temperature was 22.5°C, and relative humidity was 60%.

Since the test was to be performed under considerably high cross-head speed, the strain gauge response time was studied. Suppose a breaking strain ϵ_b of a specimen is 3%, then the total deformation $\delta_b = \epsilon_b \times L_0 = 3$ mm, where L_0 = the distance between jaws for gripping and is equal to 100 mm. (In the present experiment, the distance between jaws for gripping is taken, instead of an initial specimen length l_0.) Then the time until fracture at a high-speed tension of $V = 1000$ mm/min $= 16.7$ mm/sec is $\delta_b/V = 180$ milliseconds. On the other hand, rise time of the strain gauge itself, τ_{rg}, is less than 0.5 microsecond $+ 0.8L/C$, where $L =$ the gauge length, $C =$ the sound velocity in the specimen $= \sqrt{E/\rho}$, $E =$ Young's modulus, and $\rho =$ the density.[2] In the present case, when $L = 3$ mm and C = 1670 m/sec ($E = 340$ kg/mm^2 and $\rho = 122.4$ kg sec^2/m^4), we have $\tau_{rg} < 1.94$ microsecond $\ll 180$ milliseconds. Therefore it is easily understood that the instrument response using strain gauges assures sufficient accuracy.

RESULTS AND DISCUSSIONS

Experimental results obtained for poly(methyl methacrylate), shown in Figure 6 as an example of a brittle polymer possessing a breaking strain of about 3% at room temperature, clearly indicate the difference between two cases with and without a "slack grip," respectively, although the cross-head speed in the experiment is 1000 mm/min, which is not so high. In this case, $t_c = 0.33$ sec and $t_f = 0.22$ sec. Strain values are averages of both surfaces.

With a "slack grip," the specimen is subjected to constant strain rate, i.e., constant cross-head speed from the beginning of the tensile test, since the specimen stops until it passes through the transient cross-head speed range by use of the "slack grip." Thus, the exact and true stress–strain curve is obtained. No data scatter was observed, although six specimen pieces were tested in this case.

Without a "slack grip," the specimen subjected to tension is almost all the way under the transient strain–rate range, in other words, under nonconstant cross-head speed until fracture, since the specimen begins to elongate as soon as the cross head runs downward, and the total deformation until fracture is so small that the cross head does not have enough travel to attain the prescribed constant cross-head speed. Consequently, the stress–strain curve obtained under the variable cross-head speed differs considerably from that obtained under the prescribed, constant one. The data scatter seen was probably due to the unstable initial transient cross-head speed.

In Figure 6, the dotted line showing weighted average values without a "slack grip" denotes a deviation from the solid line showing a "slack grip" case due to the transient cross-head speed, which is lower than the prescribed constant cross-head speed achieved in the "slack grip" case. Though the present experiment for poly(methyl methacrylate) does not involve very high-speed tension (and so rather conspicuous strain rate-dependent phenomena may be hardly expected, since the strain rate dependency is much more pronounced as the cross-head speed becomes faster), nevertheless, a distinct deviation from the true curve is observed and shows that the effect of the transient cross-head speed is not negligible. As shown above, a viscoelastic specimen possessing small deformation until

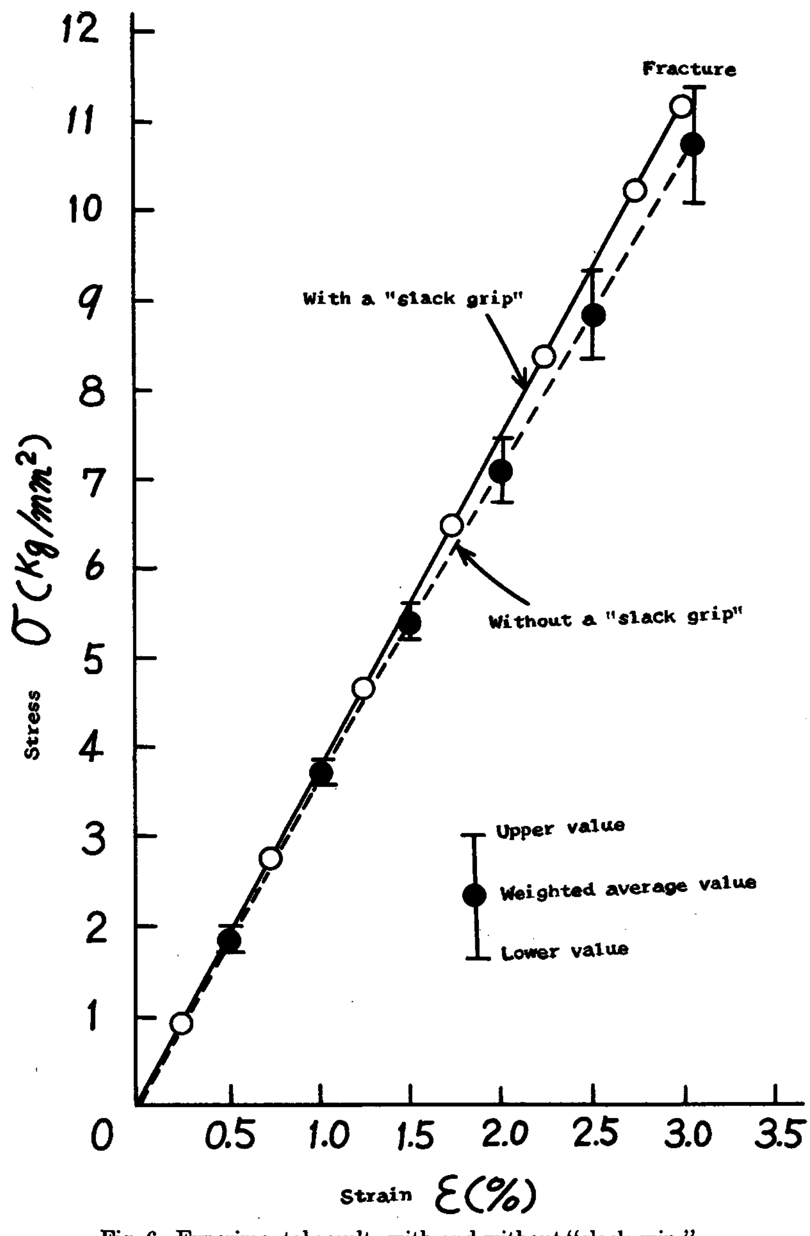

Fig. 6. Experimental results with and without "slack grip."

fracture, such as poly(methyl methacrylate), must be carefully tested so as to be subjected to the prescribed constant cross-head speed from the very start of the extension, especially in high-speed tension, since the specimen is strain rate sensitive.

The fundamental situation for brittle polymers mentioned above also obtains for brittle metals, except at high temperature, though the degree of strain rate sensitivity is not so high as in polymers. The error due to the transient cross-head speed discussed above becomes large, even for ductile polymers, if the constant strain-rate loading test is confined to the initial small elongation.

In conclusion, it is recommended that the "slack grip" be adopted for all specimen loading since an initial transient cross-head speed is inevitable with any tester, especially in high-speed tension.

CONCLUSIONS

Owing to the viscoelastic property in the material, the initial transient cross-head speed range inherent in any tensile tester affects the shape of stress–strain curves of brittle polymer, especially in high-speed tension. The concept of "slack grip" avoids this unfavorable experimental situation and always keeps the cross-head speed constant, so that stress–strain curves may be obtained at exactly constant strain rate tension from the start of tension loading. Since every existing material is viscoelastic in a strict sense, such a "slack grip" installation is recommended in cases of constant strain rate loading in high-speed tension, because of the inherent initial transient cross-head speed of all tensile testers.

The authors are grateful to Professor Kozo Kawata for his encouragement. Mr. Keizo Nosaka is acknowledged for his assistance in the experiment.

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Revised May 4, 1972