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The Effect of Strain Rate Upon the Bending Behavior of Materials

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The maximum loads sustainable in both four-point bending and prebent hinge collapse tests of several materials have been determined at crosshead rates from 4.2×10^{-3} mm/s to 4.2 m/s (10^{-2}–10^{4} in./min). All the materials exhibit a logarithmic dependence of flow stress on crosshead rate; this dependence is consistent with that previously reported for tensile deformation. Although there are some minor differences in the dynamic stress factors obtained by the bending and tensile methods, all the methods rank the materials in the same order. Thus, for materials evaluation the most convenient test method, which is usually the tensile test, can be chosen. For more complex loading geometries than considered here, scale model testing would yield the most reliable results.

1 Introduction

The design of vehicles for improved impact response, in particular the low-speed (8 km/h or 5 mph) no-damage behavior and higher speed (48 km/h or 30 mph) survivability requirements, can be served by increased knowledge of material behavior at higher strain rates. In a previous paper [1],[1] the effects of strain rate (up to 10^3/s) upon the tensile deformation and strength of a series of steels, aluminum alloys, and fiber reinforced plastics were reported. It is recognized, however, that in vehicular collisions, simple tensile deformation is rarely encountered, and bending and complex collapse of structures is usually involved. While tensile tests are easier to perform and interpret than bending tests, it is not clearly established that materials respond to high strain rates in the same way in bending as in tension. For example, we note that outer and inner fiber strains differ and thus bending at any velocity involves various strain rates.

Therefore the aim of the present investigation was to compare the response of certain materials to strain rate in tension and bending. Table 1 lists the materials tested: tensile results were reported previously [1]. Two forms of bend testing were used: (1) standard four-point bending and (2) collapse of a prebent hinge.

2 Experimental Procedure

The devices used in the four-point bending and the prebent hinge collapse experiments are shown in Figs. 1 and 2, respectively; in both fixtures test specimens are in place. Slow-speed testing (crosshead rates < 8.4 mm/s (2 in./min)) was done in an Instron testing machine, while high-speed testing (up to 21 m/s (5×10^4 in./min)) was accomplished on a MTS hydraulic test machine. All tests were performed at room temperature.

Specimens for both the four-point bending and the prebent hinge tests were prepared from sheet material 1.25 mm (0.05 in.) thick; for the four-point bending the specimens were 95.5 mm (3-3/4 in.) long by 9 mm (3/4 in.) wide, while for the prebent hinge tests the specimens were 25.4 mm (1 in.) wide. The hinge specimens were preformed in a mandrel so that the distance between compression points was 25.4 mm (1 in.), as was the distance of the hinge point to the compression axis. It was not always possible to test the hinges as formed due to either cracking (alloy 7075-T6) or extreme hardening (stainless steels) during the preforming; in these cases the alloys were heat treated to the desired condition after forming the hinge.

At crosshead rates in excess of 0.42 m/s (1000 in./min), "ringing" occurs due to the reflection of elastic stress waves in the sample, test fixture, and machine; this is manifest as oscillations in the stress-strain curve which prevent an accurate measure of the initial portion of the load-deflection curve from being obtained. The "ringing" decays rapidly so that it is possible to obtain a true load measurement at higher strains. All of the materials tested exhibited a maximum in their load deflection curves as shown in Figs. 3 and 4 for the four-point bending and the prebent hinge collapse, respectively. For the hinge configuration, the shape of the load-deflection curve varied with material due to changes in the volume of material undergoing plastic strain; however, all the curves showed a maximum. Since from energy absorption considerations we are interested in the stresses at large deformations, the maximum load was taken as a measure

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[1] Numbers in brackets designate References at end of paper.

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Table 1 Composition (wt%) of materials studied

Type of Material	C	Mn	Other Intentional Additions	Balance
Carbon Steel				
1006	0.06	0.50		Fe
1010	1.10	1.50		Fe
High Strength Low Alloy Steels				
YST-50	0.10	0.54	0.12 Ti	Fe
YST-80	0.11	0.54	0.30 Ti, 0.018V	Fe
Stainless Steels				
302	0.06	1.00	18 Cr, 8 Ni	Fe
310	0.08	1.00	25 Cr, 20 Ni	Fe
Aluminum Alloys				
6061	0.6 Si, 0.27 Cu, 1.0 Mg, 0.20 Cr			Al
7075	1.6 Cu, 2.5 Mg, 0.30 Cr, 5.6 Zn			Al
Fiberglass	approx. 30% glass fibers, 30% polyester resin, 40% inert filler.			

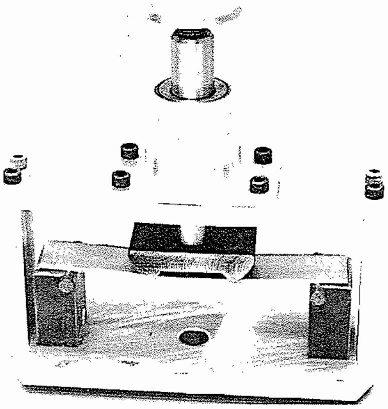

Fig. 1 Photograph of four-point bending rig with specimen in place

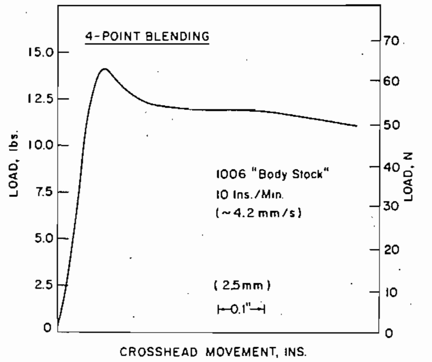

Fig. 3 Load-deflection curve for four-point bending

Fig. 2 Test rig and specimen for prebent hinge tests

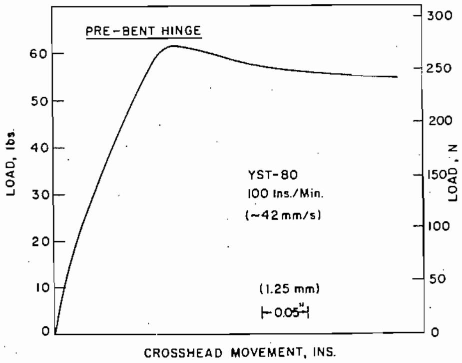

Fig. 4 Load-deflection curve for prebent hinge test

of the strength of the material. The tensile data used for comparison purposes are based upon the ultimate tensile strength, that is, the maximum tensile load observed.

For the geometry of the present four-bending fixture, the load (p) was converted to stress (σ) by the equation

$$\sigma = \frac{3P}{bd^2}$$

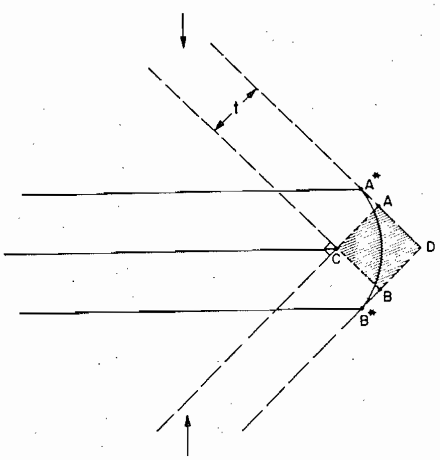

Fig. 5 Schematic for calculation of strains during collapse of prebent hinge

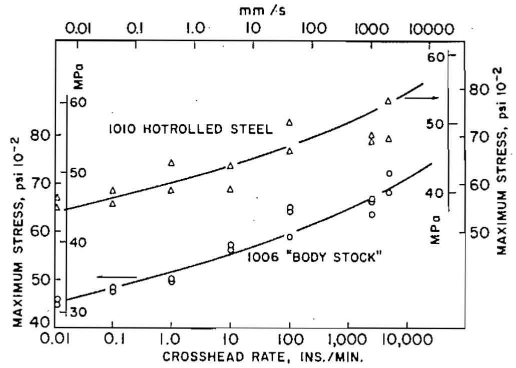

Fig. 6 Maximum stress versus crosshead rate during four-point bending of hot rolled 1010 and 1006 "body stock" steels

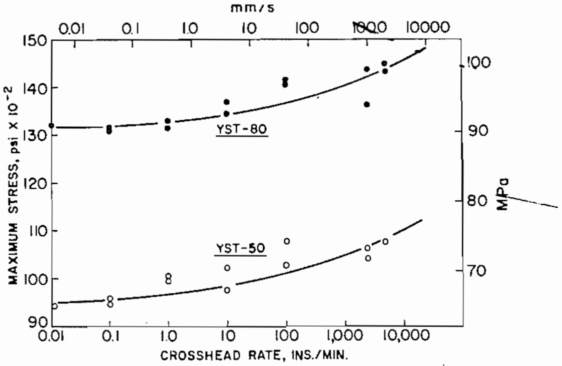

Fig. 7 Maximum stress versus crosshead rate during four-point bending of high-strength low-alloy steels YST 50 and 80

where b is the width and d is the thickness of the specimens. No attempt was made to obtain a stress measurement for the prebent hinge configuration since the main interest was the change of collapse load with crosshead rate.

To obtain an estimate of the strain rates to which the prebent hinge and four-point bending specimens were being subjected, certain assumptions were made. For the hinge it was assumed that the collapse is from the position indicated by the dotted line in Fig. 5 to the fully closed solid line and also that all of the strain is accommodated in the shaded area. A measure of the strain, ϵ, can be obtained from the change in length AB to A^*B^*.

$$\epsilon = \frac{2t - \sqrt{2}t}{\sqrt{2}t} = 0.414$$

where t is the thickness of the sheet.

Thus the strain rate, $\dot{\epsilon}$, is $(\epsilon/l_0) \cdot \dot{r}$ where l_0 is the distance between the points where the load is applied and $\dot{r}$ is the rate of closing of the loading points (i.e., crosshead rate). In the present situation with $l_0 = 25.4$ mm (1 in.), the strain rate $\simeq 1.65 \times 10^{-2}$ mm^{-1} (0.4 in.$^{-1}$) $\times$ crosshead rate; however, this is a maximum value since, as can be seen from Fig. 2, the sample does not have the idealized shape and the strain will not be as localized as assumed. The localization of the strain will depend upon the strain hardening rate of the material; a high strain hardening rate will result in the strain being spread over a larger volume.

For the four-point bending experiments the maximum tensile strain rate (for elastic deformations and small deflections) is found to be [2]

$$\dot{\epsilon} = \frac{6\,t\,\dot{r}}{(L-a)\,(L+2a)}$$

where L is the distance between the outer points, a the distance between the inner points, t the specimen thickness, and $\dot{r}$ the crosshead rate. For the present geometry the strain rate is $\sim 1.2 \times 10^{-3}$ mm^{-1} (0.03 in.$^{-1}$) $\times$ crosshead rate. Thus, for both configurations the strain rate is lower at a given crosshead rate than it was for our previous 25.4 mm (1 in.) gage length tensile samples where $\dot{\epsilon} = 4.1 \times 10^{-2}$ mm^{-1} (1.0 in.$^{-1}$) $\times \dot{r}$.

Since there is obvious uncertainty as to the validity of the assumptions used in the foregoing, our results will be simply reported as a function of crosshead rate. Since in an engineering sense we are interested in changes in load with changes in testing speed, this is sufficient. Moreover, for those concerned with the relationship of stress to strain rate, we note that as long as the results obey a semilogarithmic relationship and the strain hardening rate is approximately independent of strain rate, the stress ratio for a given strain-rate ratio will be identical to the load ratio for an equivalent change in crosshead rate.

3 Results

(a) **Four-Point Bending.** In Figs. 6–10 the maximum stress[3]

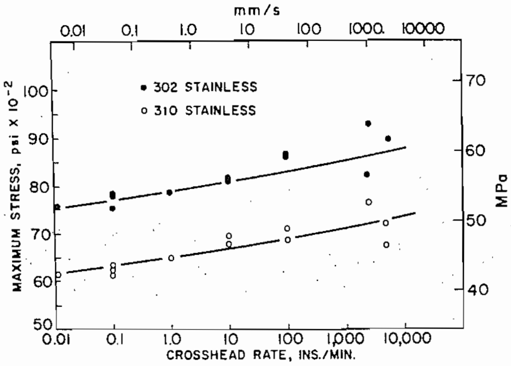

Fig. 8 Maximum stress versus crosshead rate during four-point bending of 302 and 310 stainless steels.

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[3] It should be noted that maximum stress, as used in the paper to describe the results, was calculated from the simple elastic bending formula, and may more exactly be described as maximum nominal stress.

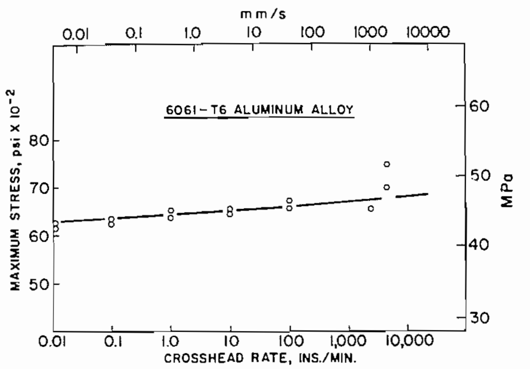

Fig. 9 Maximum stress versus crosshead rate during four-point bending of 6061-T6 aluminum alloy

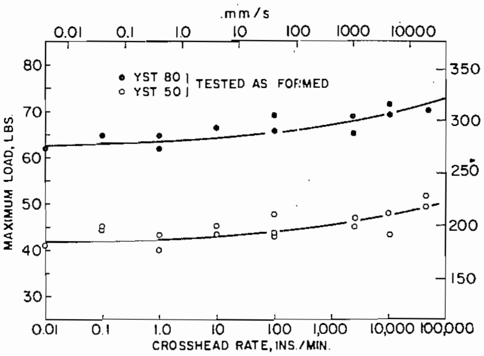

Fig. 12 Maximum load versus crosshead rate during hinge collapse of high-strength low-alloy steels YST 50 and 80

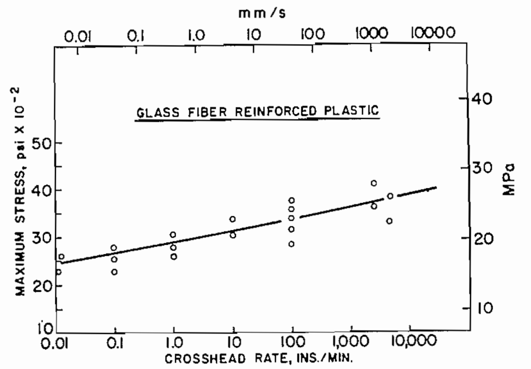

Fig. 10 Maximum stress versus crosshead rate during four-point bending of glass fiber reinforced plastic

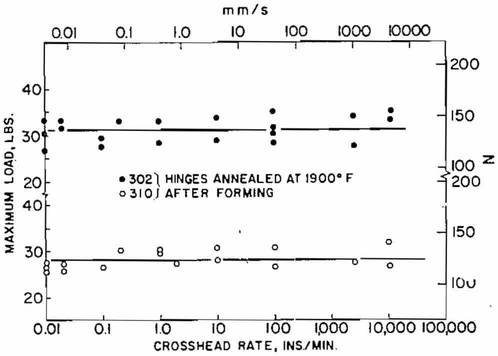

Fig. 13 Maximum load versus crosshead during hinge collapse of 302 and 310 stainless steels annealed at 1040°C after forming

is plotted as a function of the logarithm of the crosshead rate for all of the materials tested. Although not all of the results fit a simple straight-line relationship, much of the deviation can be attributed to experimental scatter. This dependence of the stress on the logarithm of the crosshead rate is in agreement with the earlier tensile results [1]. The "ringing" problem was so severe with the four-point bending apparatus at crosshead rates > 2.52 m/s (6000 in./min) that no reliable results could be obtained at higher velocities.

(*b*) **Prebent Hinge Collapse.** Figs. 11-14 give the change in maximum load as a function of log crosshead rate for the materials tested. The 302 and 310 stainless steel hinges were so work hardened by preforming that they responded elastically upon testing; annealing for 1 hr at 1040°C (1900°F) removed all the cold work put in by the prebending.

4 Discussion

The strain rate dependence is bending and prebent hinge collapse are compared to the results from the tensile tests on the same materials in Table 2; the dynamic factor is the ratio of the flow stress at 22.35 m/s (50,000 in./min, or 50 mph) to that at

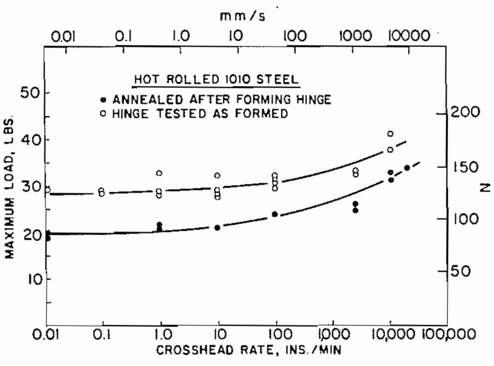

Fig. 11 Maximum load versus crosshead rate during hinge collapse of 1010 steel both as formed and annealed

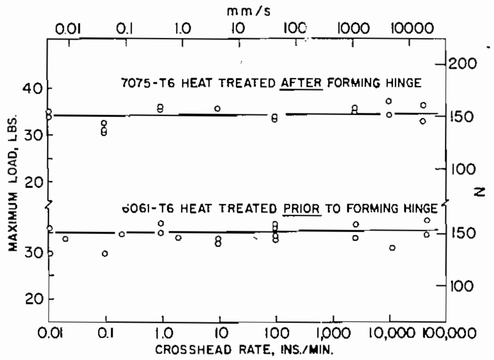

Fig. 14 Maximum load versus crosshead rate during hinge collapse of the aluminum alloys 7075-T6 heat treated after forming and 6061-T6 as formed

Table 2

Dynamic Factor

Material	Tension	Bending	Pre-bent Hinge
Carbon Steel			
1006 "Body Stock"	—	1.43	—
1010	1.37	1.35	1.48
1010 cold worked	1.19	—	1.28
High Strength Low Alloy Steels			
YST-50	1.12	1.12	1.17
YST-80	1.10	1.08	1.13
Stainless Steel			
302	1.00	1.13	1.00
310	1.12	1.16	1.00
Aluminum Alloys			
6061	1.00	1.07	1.00
7075	1.03	—	1.00
Glass Reinforced Plastic			
- fiberglass	1.55	1.42	—

0.42 mm/s (1 in./min) for the tensile and prebent hinge configurations, and the flow stress ratio between 2.24 m/s (5000 in./min) and 4.2×10^{-2} mm/s (0.1 in./min) for the four point bending. It can be seen that there is very little difference in the dynamic factors obtained by the various test methods. For the plain carbon and high-strength steels the prebent hinges give a slightly higher dynamic factor than the other procedures, but a slightly lower value for the stainless steels. However, all methods are consistent in their ranking of materials; for example, cold worked 1010 steel always has a lower dynamic factor than annealed 1010 steel, and for the high-strength low-alloy steels YST-50 has a higher dynamic factor than YST-80. Thus, it can be concluded that the same mechanism is controlling the strain-rate dependence of the materials tested by all three methods.

The present work thus confirms an earlier tentative conclusion that the rate dependence of material flow in the collapse of particular complex structures can be assessed from the rate dependence of the ultimate tensile strength. In that work, scale models of convolute frame sections were tested at a variety of speeds and the results were consistent with the rate dependence of the mild steel used in their construction [3]. The deformation in that case involved both bending and biaxial shear. The current results indicate that the same correlation of rate effects would be expected with a wide variety of materials. However, we should note that structural rate effects (due to inertia) can also be present in structural collapse and as these are not usually related to plastic deformation, then they would not correlate with the factors measured here and reported in [1].

Since the materials dynamic flow factor appears to be independent of test method, one would therefore choose to use the most convenient method for materials evaluation; usually this is the tensile test. Tensile test data are the easiest to interpret as to yield and ultimate tensile strengths, and they also provide information as to any changes in ductility or fracture mode with test speed. In addition, tensile testing is the most common test method and therefore there is a reasonable quantity of data in the literature for comparison. If a stress system more complex than either of these three so far evaluated is encountered in a component, and it is necessary to know its dynamic response, then scale-model testing would yield the most reliable results. However, if test programs are unfeasible, one can easily apply the quantitative results given in [1] to estimate the dynamic factor in the structure. The current results give us increased confidence in the engineering accuracy of this procedure.

Acknowledgments

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