Effect Of Strain Rate On Material Properties Of Sheet Steels

M. Kassar

Wei-wen Yu
Missouri University of Science and Technology, wwy4@mst.edu

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By M. Kassar[1] and W. W. Yu,[2] Fellow, ASCE

Abstract: The effect of strain rate on tensile and compressive mechanical properties of sheet steels is investigated experimentally and analytically. Three sheet steels are studied in both longitudinal and transverse directions under different strain rates and different amounts of prior cold stretching. In order to determine the separate effects of strain rate and aging, half of the cold-stretched coupons are tested in an average of two days after cold-stretching operation. The remaining half are tested to failure at least 30 days after cold-stretching operation. The results show that the proportional limit, yield strength, and ultimate strength increase with increasing strain rate. In general, the amount of increase is found to be: (1) Dependent on the material static yield strength and possibly the F_u/F_y ratio, the amounts of prior cold stretching, and/or the strain rates used in the tests; and (2) independent of test directions (longitudinal or transverse), test types (tension or compression), and/or material aging conditions (aged or nonaged). The yield strength is found to be more sensitive to strain rate than the ultimate strength was.

Introduction

The effect of the strain rate on the mechanical behavior of steels has long been a subject of interest to researchers. It is well known that the steel mechanical properties such as proportional limit, yield strength, and ultimate strength increase with increasing strain rate (Manjoine 1944; Norris et al. 1959; Holt 1962; Chatfield and Rote 1974). It was also found that the ultimate strength is less sensitive to strain rate than the yield strength was (Winlock and Leiter 1937). However, the modulus of elasticity (Soroushian and Choi 1987) and total elongation (Chatfield and Rote 1974) may not be significantly influenced by strain rate. The quasi-static mechanical properties of steels are obtained at a strain rate about 0.0001 in./in./sec (0.0001 mm/mm/s). These properties may be different when tested at different strain rates.

The sensitivity of materials to strain rate is different from one material to the other. This sensitivity is usually measured by the slope of the line of yield stress versus strain rate in a logarithmic scale. In general, the steel materials are more sensitive to strain rate than aluminum is. The strain-rate sensitivity for stainless steel is a constant (Kassner and Breithaupt 1984), while it increases with increasing strain rate for carbon steel (Sachdev and Wagonar 1983). The strain-rate sensitivity was found to be insensitive to changes in steel microstructures (Nagorka 1987).

In addition to the effect of strain rate on the mechanical properties of materials, the history of loading can affect the flow stresses at a given strain and strain rate. A technique that has achieved popularity over the last decade is the jump test, for which a specimen is subjected to a slow rate of loading followed by a very high loading rate (Zukas et al. 1982). Despite the steel

[1]Prin. Engr., ABB Impell Corp., 1333 Butterfield Road, Suite 550, Downers Grove, IL 60515.

[2]Curators' Prof. of Civ. Engrg., Univ. of Missouri–Rolla, Rolla, MO 65401.

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sensitivity to strain rate, it was found that it is insensitive to strain-rate history (Wilson et al. 1979; Eleiche and Campbell 1976).

Recently, a research project was conducted at the University of Missouri-Rolla (UMR) under the sponsorship of the American Iron and Steel Institute (AISI). The main purpose of the project was to determine the effect of strain rate on material properties of sheet steels (phase I) and the structural strength of cold-formed steel members (phase II). The test data developed from this study may assist automotive engineers to achieve a more economical design for vehicle components under impact conditions.

This paper presents the results of the first phase of the AISI-sponsored project, which included testing the three selected sheet steels in tension and compression under different strain rates. Comparisons between the tested static and dynamic mechanical properties for these materials are presented herein. The preliminary findings of the effect of strain rate on structural strength of cold-formed steel members (phase II) are discussed in a subsequent paper (Kassar et al. 1992).

Experimental Investigation

Three sheet steels (35XF, 50XF, and 100XF) with nominal yield strengths ranging from 35 to 100 ksi (241 to 690 MPa) were studied experimentally in tension and compression under different strain rates and different amounts of prior cold stretching. The thicknesses and chemical compositions for these materials are listed in Table 1. The strain rate ranged from 0.0001 to 1.0 in./in./sec (0.0001 to 1.0 mm/mm/s). The amounts of uniform prior cold stretching used for the tests were 0.02 in./in. (20 mils) and 0.08 in./in. (80 mils). A total of 124 tensile coupons and 54 compressive coupons were tested in this study.

Test Specimens

All tensile and compressive coupon tests were tested following the procedures outlined in the ASTM specifications E8-69 and E9-70, respectively. Fig. 1 shows the tensile specimen dimensions while Fig. 2 shows the compressive specimen dimensions selected to fit a Montgomery-Templin compression test fixture. The notches along one edge of the compressive specimen were for the installation of the compressometer knife edges.

Equipment

All tensile and compressive specimens were tested in a 110 kips (489 kN) MTS 880 material test system (MTS) located in the UMR engineering research laboratory. This testing machine is a servohydraulic closed-loop type

TABLE 1. Chemical Compositions of Sheet Steels Used

AISI designation (1)	Thickness (in.) (2)	*C* (3)	*Mn* (4)	*P* (5)	*S* (6)	*Si* (7)	*V* (8)	*Cu* (9)	*Al* (10)	*Cb* (11)	*Zr* (12)
035XF	0.085	0.070	0.40	0.007	0.017	—	0.08	—	—	—	—
050XF	0.077	0.081	0.96	0.017	0.003	0.27	—	—	0.04	—	—
100XF	0.062	0.070	0.43	0.006	0.023	—	—	0.11	0.056	0.064	0.08

Note: 1 in. = 25.4 mm; 035XF is hot-rolled sheet steel; 0.50XF is cold-rolled sheet steel; and 100XF is cold-rolled sheet steel.

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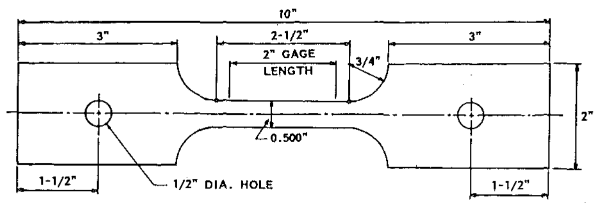

FIG. 1. Nominal Dimensions of Tensile Coupons Used for 100XF, 50XF, and 35XF Sheet Steels

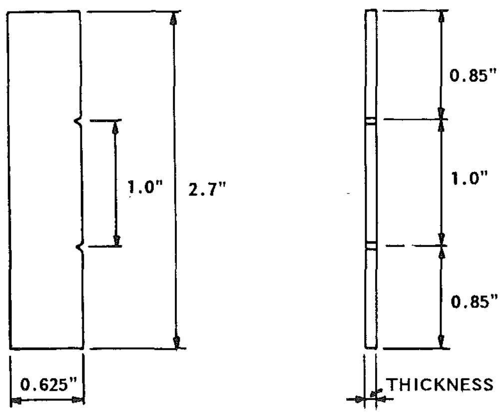

FIG. 2. Nominal Dimensions of Compressive Coupons Used for 100XF, 50XF, and 35XF Sheet Steels

with three modes of operation, commonly referred to as stroke, strain, and load. Figs. 3 and 4 show the test system along with the remaining equipment used for the tensile and compressive tests, respectively. The load was measured by an MTS system model 380041-06 load cell and associated conditioning, which was calibrated prior to testing according to the procedure of the National Bureau of Standards. An MTS extensometer with a 2-in. (50.8 mm) gage length was used to measure the tensile strains from zero to failure while on MTS compressometer with 1-in. (25.4-mm) gage length was used to measure the compressive strains from 0 to 0.02 in./in. (0.02 mm/mm). Fig. 5 shows the tensile test setup and the attachment of the extensometer. In Fig. 6, the test fixtures used to conduct the compressive tests are shown. They are: (1) Compression subpress; (2) compression jig, which contains rollers to support the specimen from both sides and to prevent it from buckling during the test; (3) MTS compressometer; and (4) test specimen.

The data-acquisition system used to obtain the test data conforms to computer automated measurements and control (CAMAC) standards. The main data-acquisition module used in this system is a kinetic systems model 4022 transient recorder. The unit has 64 simultaneous sampling input channels. The unit is capable of acquiring sets of data at the maximum rate of 25,000 sets of readings per second for each of the 64 channels. After the data has been acquired, it is downloaded into a 10,000 Data General minicomputer for analysis. The transient recorder includes a direct readout for "present value" monitoring, which allows the data to be displayed in real time as the test runs.

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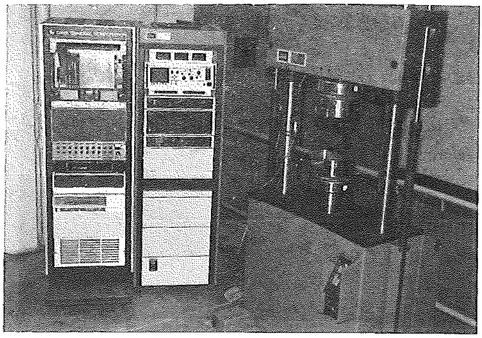

FIG. 3. Material Test System (MTS) 880 Used for Tensile Tests

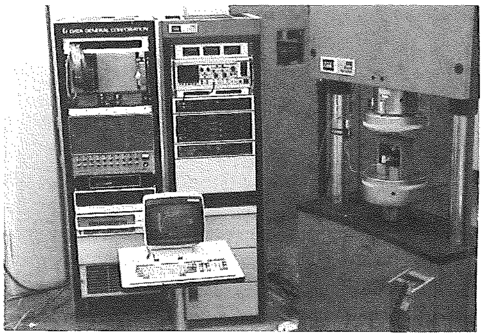

FIG. 4. Test Setup for Compressive Tests

Test Procedure

Tensile Tests

Prior to testing, the dimensions of the tensile specimen were measured to the nearest 0.001 in. (0.0254 mm) and the gage length (2 in.) (50.8 mm) was marked in ink. The specimen was then placed in the MTS grips such that the longitudinal axis of the specimen coincided with the centerline of the grips. Next, the extensometer was attached to the specimen such that the extensometer knife edges lined up with the gage marks. The function generator was then programmed to produce the desired ramp. The slope of this ramp equals to the strain rate selected for the test. The maximum test time was programmed to be 5,000 sec for the strain rate of 0.0001 in./in./sec (0.0001 mm/mm/s), 50 sec for the strain rate of 0.01 in./in./sec (0.01 mm/mm/s), and 0.5 sec for the strain rate of 1.0 in./in./sec (1.0 mm/mm/s). In all tests, the strain mode was selected as the control mode.

A constant strain rate is very difficult to maintain with the conventional testing machine, especially at high strain rate. The strain rate was controlled electronically by the MTS 880 test system, which allowed the planned strain rate to be achieved without great difficulty.

The cold-stretched coupons were loaded to the desired 2% strain or 8% strain by letting the span in the MTS controller stop the test when the

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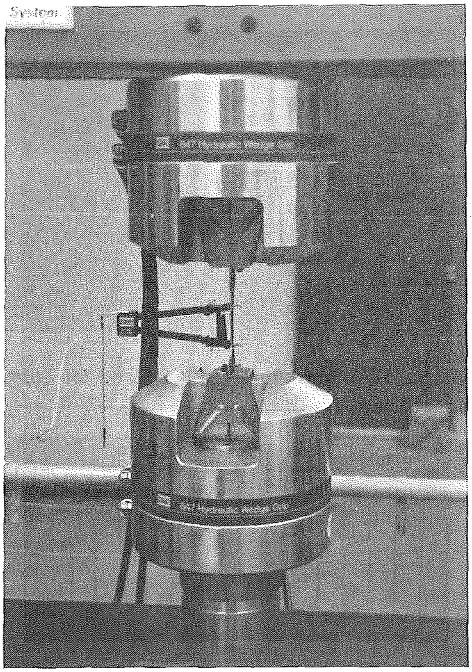

FIG. 5. Tensile Test Setup Showing Attachment of Extensometer

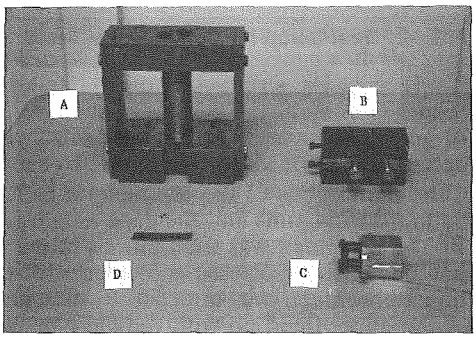

FIG. 6. Fixtures Used in Compressive Tests

desired strain was reached. Then the specimen was unloaded and reloaded to failure at a later date.

Compressive Tests

The compressive test procedures are similar to those used for tensile tests except that MTS compression platens and a special specimen-supporting fixture were used. First, the specimen was placed in the Montgomery-Templin fixture and the lateral roller supports of the fixture were tightened against both sides of the specimen. Next, the MTS compressometer was

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attached to the specimen such that the knife edges of the compressometer smoothly inserted into the notches of the compression specimen. Then, with the specimen, test fixture, and compressometer attached together as a unit, the entire unit was placed in the compression subpress. Next step was to place the subpress between the compression platens of the MTS loading frame. The strain mode was used as a control mode to maintain a constant strain rate. The maximum test time was programmed to be 20 sec for the strain rate of 0.0001 in./in./sec (0.0001 mm/mm/s), 2.0 sec for the strain rate of 0.01 in./in./sec (0.01 mm/mm/s), and 0.02 sec for the strain rate of 1.0 in./in./sec (1.0 mm/mm/s).

Results of Tests

A total of 54 compressive tests and 124 tensile tests were conducted under different strain rates for the three selected steel materials. The stress-strain curves were plotted by using the Data General graphics software named *Trendview* with the stress-strain data recalled from the computer storage. Figs. 7–9 present typical stress-strain curves for the three virgin materials (35XF, 50XF, and 100XF) tested in longitudinal tension under different strain rates. As shown in these figures, the stress-strain curves of 100XF and 50XF steels are sharp-yielding–type curves while the stress-strain curves of 35XF steel are gradual-yielding–type curves.

In order to study the effects of cold-stretching and aging with the strain rate on the mechanical properties of 50XF steel in longitudinal tension, Figs. 10–12 compare three stress-strain curves with different amounts of prior cold stretching tested at a constant strain rate. It is observed from these figures that the stress-strain curves of 50XF sheet steel became a gradual-yielding–type curve after the material was cold stretched to a selected strain of 2%, but was a sharp-yielding–type curve for 8% prestrain.

The tensile and compressive stress-strain curves for other cases of the virgin materials, as well as for the materials with different amounts of cold-stretching tested in longitudinal or transverse direction under different strain rates, were presented by Kassar and Yu (1989a, 1989b).

Evaluation of Experimental Data

The test results indicate that most of mechanical properties are affected by the strain rate and the amount of prior cold stretching. Tables 2 and 3 compare the dynamic mechanical properties determined at the strain rate of 1.0 in./in./sec and the static properties determined at the strain rate of 0.0001 in./in./sec. The effects of strain rate on proportional limit, yield stress, and tensile strength are discussed next.

Proportional Limit

The proportional limits (F_{pr}) are obtained for compression tests using 0.01% offset method as illustrated in Fig. 13. The proportional limits of sheet steels tested in compression increased with the strain rate. Table 4 lists average, tested compressive proportional limit of the three sheet steels studied in this investigation. The percentage increases in proportional limits for the three materials studied in compression are: 9–24% for 100XF steel, 4–22% for 50XF steel, and 14–24% for 35XF steel when the strain rate increased from 0.0001 to 0.01 in./in./sec (0.0001 to 0.01 mm/mm/s).

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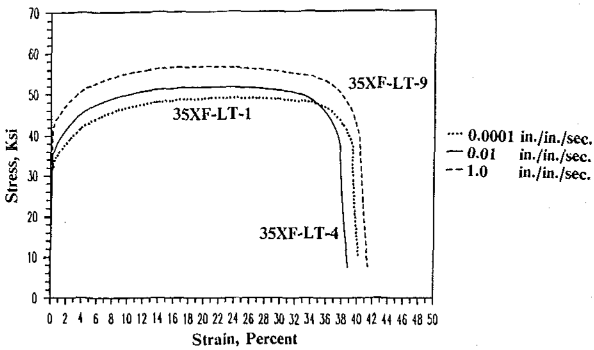

FIG. 7. Stress-Strain Curves for 35XF Sheet Steel under Different Strain Rates

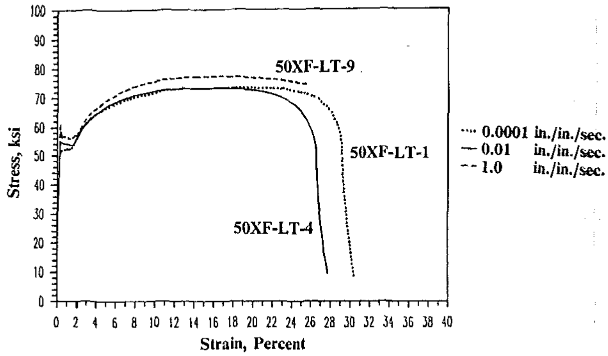

FIG. 8. Stress-Strain Curves for 50XF Sheet Steel under Different Strain Rates

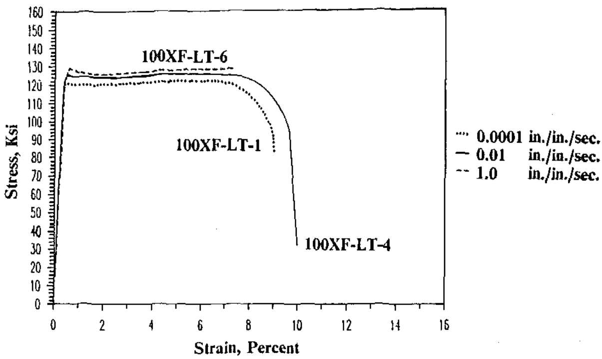

FIG. 9. Stress-Strain Curves for 100XF Sheet Steel under Different Strain Rates

Yield Strength

The yield strength (F_y) of the sharp-yielding steel was determined as the stress where the stress-strain curve becomes horizontal. For the gradual-yielding–type stress-strain curves as shown in Fig. 13, the yield strength was determined by the intersection of the stress-strain curve and the straight

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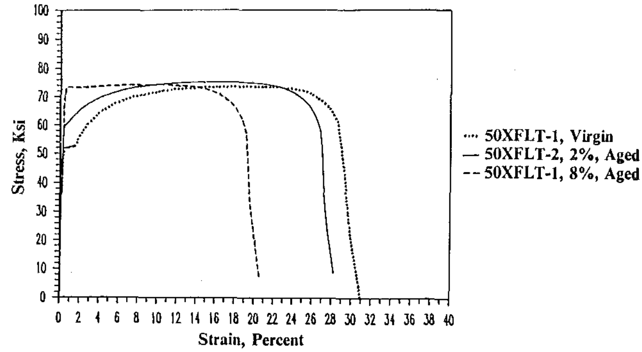

FIG. 10. Stress-Strain Curves for 50XF Steel with Different Amounts of Prior Cold Stretching Tested at Strain Rate of 0.0001 in./in./sec (0.0001 mm/mm/s)

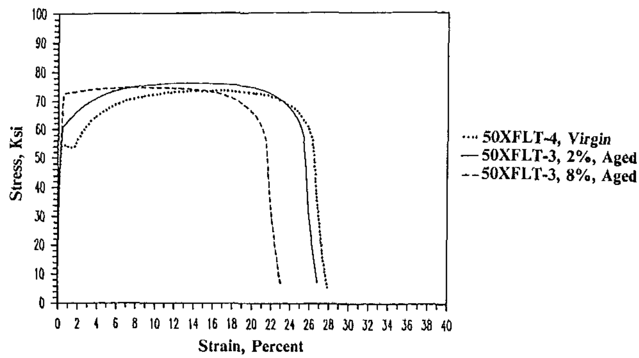

FIG. 11. Stress-Strain Curves for 50XF Steel with Different Amounts of Prior Cold Stretching Tested at Strain Rate of 0.01 in./in./sec (0.01 mm/mm/s)

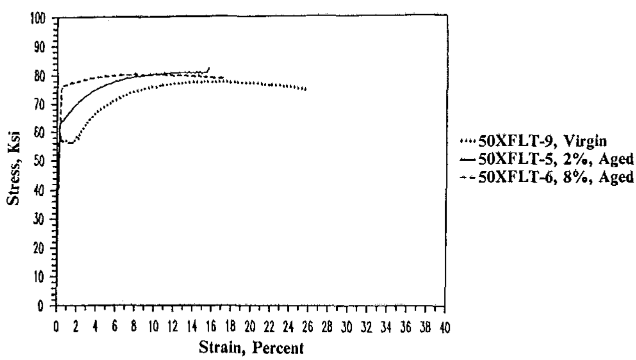

FIG. 12. Stress-Strain Curves for 50XF Steel with Different Amounts of Prior Cold Stretching Tested at Strain Rate of 1.0 in./in./sec (1.0 mm/mm/s)

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TABLE 2. Ratios of Dynamic to Static Tensile Mechanical Properties for Three Sheet Steels

Type of sheet steel (1)	$(F_y)_s$ (ksi) (2)	$(F_u)_s$ (ksi) (3)	(Elongation)$_s$ (4)	$(F_y)_d/(F_y)_s$ (5)	$(F_u)_d/(F_u)_s$ (6)	(Elongation)$_d$/(Elongation)$_s$ (7)	Number of tests (8)
100XF-LT-virgin	124.2	124.2	9.5	1.04	1.04	—	7
100XF-TT-virgin	137.8	137.8	4.9	1.04	1.04	1.30	6
50XF-LT-virgin	49.50	72.97	31.0	1.10	1.08	0.80	9
50XF-LT-2%, N.A.	56.40	73.01	27.0	1.11	1.10	1.00	6
50XF-LT-8%, N.A.	71.54	73.86	24.2	1.08	1.10	0.85	6
50XF-LT-2%, aged	59.23	75.07	29.0	1.07	1.08	0.99	6
50XF-LT-8%, aged	73.13	73.81	20.0	1.04	1.07	—	6
50XF-TT-virgin	50.59	73.44	26.7	1.10	1.09	1.04	9
50XF-TT-2%, N.A.	59.29	74.90	23.1	1.15	1.09	1.06	2
50XF-TT-8%, N.A.	73.65	75.88	21.8	1.06	1.08	0.85	4
50XF-TT-2%, aged	60.27	75.05	27.7	1.07	1.11	0.80	4
50XF-TT-8%, aged	74.3	74.95	19.3	1.05	1.09	0.92	4
35XF-LT-virgin	32.87	49.35	38.9	1.29	1.15	1.05	9
35XF-LT-2%, N.A.	39.55	49.47	37.7	1.20	1.15	1.04	6
35XF-LT-8%, N.A.	46.31	49.25	29.7	1.14	1.16	1.18	6
35XF-LT-2%, aged	39.95	49.71	33.8	1.19	1.14	1.14	6
35XF-LT-8%, aged	46.15	48.65	32.7	1.16	1.18	0.96	6
35XF-TT-virgin	33.51	49.30	36.2	1.29	1.13	0.98	6
35XF-TT-2%, N.A.	38.10	47.95	33.6	1.22	1.17	1.04	4
35XF-TT-8%, N.A.	45.45	47.79	25.6	1.15	1.18	1.08	4
35XF-TT-2%, aged	39.08	48.81	30.8	1.15	1.14	1.09	4
35XF-TT- 8%, aged	45.45	47.63	27.0	1.12	1.17	1.05	4

Note: LT = longitudinal tension; TT = transverse tension; and N.A. = nonaged condition.

TABLE 3. Ratios of Dynamic to Static Compressive Yield Strengths for Three Sheet Steels

Type of sheet steel (1)	$(F_y)_s$ (ksi) (2)	$(F_y)_d/(F_y)_s$ (3)	Number of tests (4)
100XF-LC	107.29	1.07	9
100XF-TC	123.66	1.07	9
50XF-LC	49.68	1.10	9
50XF-TC	51.08	1.09	9
35XF-LC	29.83	1.24	9
35XF-TC	32.62	1.33	9

Note: LC = longitudinal compression; and TC = transverse compression.

line drawn parallel to the elastic portion of the stress-strain curve at an offset of 0.002 in./in. (0.002 mm/mm). In Tables 2 and 3, the dynamic yield strength, $(F_y)_d$, and the static yield strength, $(F_y)_s$, are compared by using a ratio of $(F_y)_d/(F_y)_s$. In the aforementioned expressions, $(F_y)_d$ is the yield

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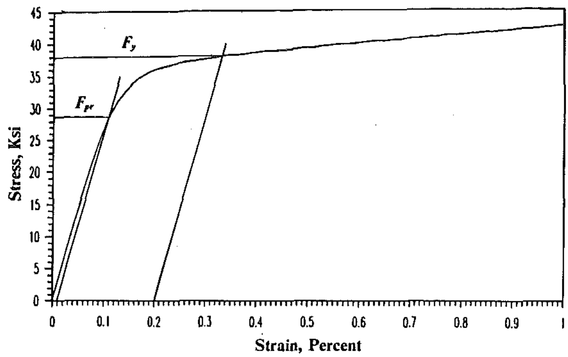

FIG. 13. Typical Stress-Strain Curve for Determination of Mechanical Properties for 35XF Steel Material

TABLE 4. Average Tested Compressive Proportional Limit for 100XF, 50XF, and 35XF Sheet Steels

Type of Sheet Steel (1)	Proportional Limit (ksi) Under strain rate of 0.0001 in./in./sec/(0.0001 mm/mm/s) (2)	Proportional Limit (ksi) Under strain rate of 0.01 in./in./sec (0.01 mm/mm/s) (3)
100XF-LC	71.25	88.44
100XF-TC	103.66	113.45
50XF-LC	38.64	40.05
50XF-TC	41.51	50.65
35XF-LC	17.79	20.03
35XF-TC	23.12	28.73

Note: LC = longitudinal compression; and TC = transverse compression.

strength determined for the strain rate of 1.0 in./in./sec (1.0 mm/mm/s) while $(F_y)_s$ is the yield strength determined for the strain rate of 0.0001 in./in./sec (0.0001 mm/mm/s). It can be seen that for all cases, the yield strength of sheet steel increases with the strain rate. The increases in yield strength for the three steels studied in tension are: 4% for 100XF steel, 4–15% for 50XF steel, and 12–29% for 35XF steel, while the percentage increases in yield strength for the three steels studied in compression are: 7% for 100XF steel, 9–10% for 50XF steel, and 24–33% for 35XF steel when the strain rate increased from 0.0001 to 1.0 in./in./sec (0.0001 to 1.0 mm/mm/s).

It is observed from these tables that the increases in tensile yield strength for the virgin materials are independent of the test direction (longitudinal or transverse). However, for 35XF steel tested in compression, the increase in yield stress in the transverse direction is larger than that in the longitudinal direction. It is also noted that the percentage increase in proportional limit obtained from compression test are larger than the percentage increase in yield stress when the strain rate increased from 0.0001 to 0.01 in./in./sec (0.0001 to 0.01 mm/mm/s) (see Table 4). The effect of the strain rate on yield strength decreases as the static yield stress and/or the amount of cold

stretching increases. Previous study (Chajes et al. 1963) indicated that the increase in yield strength due to cold work is caused mainly by strain hardening and strain aging. However, in the present investigation no significant increase in yield strength was observed due to the strain-aging effect for the steels used in this phase of study. It was also observed that strain aging has little or no effect on the type of stress-strain curve for the materials tested.

Ultimate Strength

The ultimate tensile strength (F_u) was determined from each of the tensile tests as the maximum stress that the given tensile coupon could withstand before fracture. Similar to the effect of strain rate on yield strength, the ultimate tensile strengths of sheet steels increased with the strain rate. The increases in ultimate tensile strengths for the three materials studied in tension, as shown in Table 2, are: 4% for 100XF steel, 7–11% for 50XF steel, and 13–18% for 35XF steel when the strain rate increased from 0.0001 to 1.0 in./in./sec (0.0001 to 1.0 mm/mm/s). The ultimate compressive strengths could not be obtained because the buckling of the unsupported lengths at each end of the compressive specimen limited the obtainable range of the stress-strain curves to approximately 1.8%. It is noted from Table 2 that the amounts of increase in ultimate tensile strength due to the increase in strain rate are approximately the same for both longitudinal and transverse tension.

Strain-Rate Sensitivity

The relation between the stress and the strain rate (Chatfield and Rote 1974) at a given strain can be expressed as follows:

$$\sigma = C\dot{\epsilon}^m \quad (1)$$

By applying (1) to two different strain rates and eliminating C, we have:

$$m = \frac{\ln\left(\frac{\sigma_2}{\sigma_1}\right)}{\ln\left(\frac{\dot{\epsilon}_2}{\dot{\epsilon}_1}\right)} \quad (2)$$

for two given values of the flow stress of a material at two different strain rates. The strain-rate sensitivity exponent m may be calculated by using (2).

Tables 5 and 6 list the values of the strain-rate sensitivities, which were calculated on the basis of (2). The value of m_1 was calculated for the yield strengths corresponding to the strain rates of 0.0001 and 0.01 in./in./sec (0.0001 and 0.01 mm/mm/s), while the value of m_2 was calculated for the yield strengths corresponding to the strain rates of 0.01 and 1.0 in./in./sec (0.01 and 1.0 mm/mm/s). In Table 5, whenever only two strain rates were used in the tests, the value of m_3 was calculated for the yield strengths corresponding to the strain rates of 0.0001 and 1.0 in./in./sec (0.0001 and 1.0 mm/mm/s). From Tables 5 and 6, it can be seen that, in general, the value of m in tension and compression increases as the strain rate increases. The strain-rate sensitivity decreases progressively as the static-yield strength level increases. For tension tests with different amounts of cold stretching, the strain-rate sensitivity decreases as the amount of cold stretching increases.

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TABLE 5. Values of Strain-Rate Sensitivities m for Three Sheet Steels Based on Changes of Yield Strengths at Different Strain Rates (Tensile Tests)

Type of sheet steel (1)	m_1 (2)	m_2[b] (3)	m_3[c] (4)
100XF-LT-virgin	0.003	0.005	0.004
100XF-TT-virgin	0.003	0.006	0.004
50XF-LT-virgin	0.009	0.013	0.011
50XF-LT-2%, nonaged	0.009	0.014	0.011
50XF-LT-8%, nonaged	0.009	0.009	0.009
50XF-LT-2%, aged	0.005	0.009	0.007
50XF-LT-8%, aged	0.000	0.008	0.004
50XF-TT-virgin	0.011	0.009	0.010
50XF-TT-2%, nonaged	—	—	0.016
50XF-TT-8%, nonaged	—	—	0.006
50XF-TT-2%, aged	—	—	0.008
50XF-TT-8%, aged	—	—	0.005
35XF-LT-virgin	0.022	0.033	0.027
35XF-LT-2%, nonaged	0.015	0.023	0.019
35XF-LT-8%, nonaged	0.013	0.016	0.014
35XF-LT-2%, aged	0.008	0.029	0.019
35XF-LT-8%, aged	0.014	0.018	0.016
35XF-TT-virgin	0.018	0.037	0.028
35XF-TT-2%, nonaged	—	—	0.021
35XF-TT-8%, nonaged	—	—	0.015
35XF-TT-2%, aged	—	—	0.016
35XF-TT-8%, aged	—	—	0.013

[a]m_1 = strain-rate sensitivity based on changes of yield stress between strain rates of 0.0001 and 0.01 in./in./sec (0.0001 and 0.01 mm/mm/s).
[b]m_2 = strain-rate sensitivity based on changes of yield stress between strain rates of 0.01 and 1.0 in./in./sec (0.01 and 1.0 mm/mm/s).
[c]m_3 = strain-rate sensitivity based on changes of yield stress between strain rates of 0.0001 and 1.0 in./in./sec (0.0001 and 1.0 mm/mm/s).

TABLE 6. Values of Strain-Rate Sensitivities for Three Sheet Steels Based on Changes of Yield Strengths at Different Strain Rates (Compressive Tests)

Type of sheet steel (1)	m_1 (2)	m_2 (3)
100XF-LC	0.008	0.007
100XF-TC	0.004	0.009
50XF-LC	0.012	0.009
50XF-TC	0.010	0.008
35XF-LC	0.015	0.031
35XF-TC	0.025	0.037

[a]m_1 = strain-rate sensitivity based on changes of yield stress between strain rates of 0.0001 and 0.01 in./in./sec (0.0001 and 0.01 mm/mm/s).
[b]m_2 = strain-rate sensitivity based on changes of yield stress between strain rates of 0.01 and 1.0 in./in./sec (0.01 and 1.0 mm/mm/s).

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Prediction of Yield Strength for High Strain Rates

Fig. 14 compares the average values of tensile yield strengths for the three materials (35XF, 50XF, and 100XF) in the virgin condition and tested in the longitudinal direction under different strain rates. The data plotted in this figure are in terms of yield stress versus logarithmic strain rate. For each case, the following second-degree polynomial was developed using the least-square method for the strain-rate range of 0.0001–1.0 in./in./sec (0.0001–1.0 mm/mm/s).

$$Y = A + BX + CX^2 \quad \ldots \quad (3)$$

The polynomial parameters A, B, and C are given at the top of the curve for each case. The values of yield strengths of the steels used in this investigation at higher strain rate (larger than 1.0 in./in./sec [1.0 mm/mm/s] and

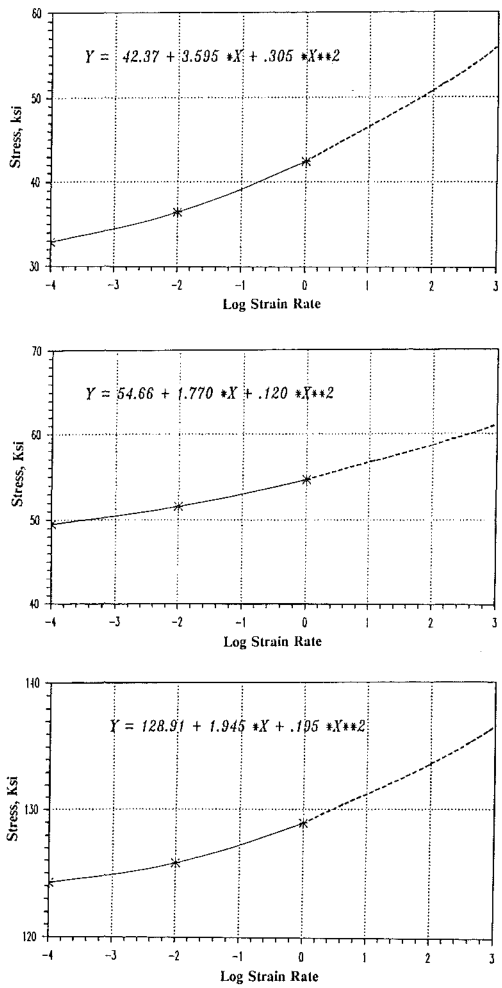

FIG. 14. Tensile Yield Stress versus Logarithmic Strain Rate Curves

up to 1,000 in./in./sec [1,000 mm/mm/s]) could be extrapolated by using the equation or the curve for each individual case.

The polynomial constants A, B, and C are presented by Kassar and Yu (1989*b*) for other cases such as: ultimate strength for coupons tested in longitudinal direction, yield and ultimate strengths for coupons tested in transverse direction, and yield and ultimate strengths for the three materials tested in both directions with different amounts of prior cold stretching under different strain rates.

CONCLUSIONS

The following conclusions are drawn from this study of the effect of strain rate on material properties of the sheet steels tested in the present investigation:

1. Proportional limit, yield strength, and ultimate strength increase with increasing strain rate.
2. Yield strength is more sensitive to strain rate than the ultimate strength is.
3. The strain-rate sensitivity value for sheet steels is not a constant. In most cases, it increases with increasing strain rate.
4. For the materials used in this investigation, the mechanical properties of sheet steels having low yield strengths are more sensitive to strain-rate effects.
5. A second-degree polynomial is well fitted to the experimental data for both tension and compression, and can be used to predict the yield and ultimate strengths at high strain rates above the range of the strain rate used in the tests.

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Appendix II. Notation

The following symbols are used in this paper:

A, B, C = constants;
F_{pr} = proportional limit;
F_y = yield strength;
$(F_y)_d$ = dynamic yield strength;
$(F_y)_s$ = static yield strength;
F_u = ultimate strength;
$(F_u)_d$ = dynamic ultimate strength;
$(F_u)_s$ = static ultimate strength;
m = strain rate sensitivity;
$\dot{\varepsilon}$ = strain rate; and
σ = true or engineering stress.