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Design of automotive structural components using high strength sheet steels the effect of strain rate on mechanical properties of sheet steels

Maher Kassar
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DESIGN OF AUTOMOTIVE STRUCTURAL COMPONENTS USING HIGH STRENGTH SHEET STEELS

THE EFFECT OF STRAIN RATE ON MECHANICAL PROPERTIES OF SHEET STEELS

by

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Research Assistant

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Project Director

A Research Project Sponsored by the American Iron and Steel Institute

January 1989

Department of Civil Engineering
University of Missouri-Rolla
Rolla, Missouri
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I. INTRODUCTION

During recent years, automotive manufacturers have produced lighter vehicles for the purpose of achieving fuel economy. To accomplish the construction of such automobiles, high strength sheet steels with various yield strengths up to 190 ksi have been used for auto parts and structural components\textsuperscript{1-9}.

In order to provide some technical assistance for the design of such high strength steels, the first edition of the "Guide for Preliminary Design of Sheet Steel Automotive Structural Components" was issued by American Iron and Steel Institute (AISI) in February 1981.\textsuperscript{10} The use of the Guide was discussed by Errera at the SAE International Congress and Exposition held in Detroit, Michigan in February 1982.\textsuperscript{5} In view of the fact that the design information contained in this document can be used only for sheet steels with yield strengths of up to 80 ksi, a research project has been conducted at the University of Missouri-Rolla (UMR) since 1982 to study the structural strength of automotive components using high strength sheet steels. In the first phase of the UMR program, typical mechanical properties and representative stress-strain curves were established by a series of static tests for different grades of sheet steels with yield strengths ranging from 49 to 164 ksi. The second phase of the UMR project was directed toward the web crippling strength of beam webs and the strength of members consisting of flat and curved elements. The research findings were presented in ten progress reports\textsuperscript{11-20}. In addition, the effective design widths of high strength cold-formed steel members were also investigated\textsuperscript{21}. Some of the research results were used
in the first edition of the AISI Automotive Steel Design Manual published in 1986\textsuperscript{59}. This Manual brings together material properties, product design, and manufacturing information to make the most effective use of sheet steels with yield strengths of up to 140 ksi. The contents and use of the Design Manual were discussed by Cowie and Lutz at the 1987 SAE International Congress and Exposition\textsuperscript{22-23}.

Because the previous UMR studies were limited only to the tests subject to static loads and it is well known that the yield strength, tensile strength, and the stress-strain relationship of sheet steels are affected by the rate of strain used for the tests, additional research work was conducted at the University of Missouri-Rolla in 1988. This study primarily involved the experimental determination of the dynamic material properties of three selected sheet steels with nominal yield strengths ranging from 35 to 100 ksi under different strain rates. The strain rates ranged from $10^{-4}$ to 1.0 in./in./sec. All tests were performed at UMR Engineering Research Laboratory by using the new MTS 880 Test System. The test data developed from this work will be used for the evaluation of future member tests on the design of automotive components.

This study began with a review of the available literature on stress-strain curves of sheet steels and the effects of the strain rate and strain rate history on the mechanical properties of sheet steels. The literature survey is presented in Section II. Section III presents the detailed information obtained from 124 tension tests. This Section also discusses the strain rate effects on the mechanical properties of the sheet steels tested. Finally, the research findings are summarized in Section IV.
II. REVIEW OF LITERATURE

A. MECHANICAL PROPERTIES OF SHEET STEELS

1. Engineering Stress-Strain Curves. The stress-strain curve is the relationship between the stress and the corresponding strain. For engineering stress-strain curves, the stress, \( f \), is measured by the load, \( P \), divided by the original, unreduced area, \( A_o \), of the specimen, i.e.

\[
f = \frac{P}{A_o}
\]  

(2.1)

The engineering strain, \( \epsilon \), is the difference between the original, unreduced gage length, \( l_o \), and the deformed length, \( l \), divided by the original length, i.e.

\[
\epsilon = \frac{(l-l_o)}{(l_o)}
\]  

(2.2)

For high strength sheet steels, the two basic types of engineering stress-strain (f-\( \epsilon \)) curves are gradual and sharp yielding as shown in Figure 2.1.\(^{24} \) The classification of the f-\( \epsilon \) curve is based on the yielding behavior of the steel. As a general rule, hot-rolled sheet steels tend to be sharp yielding (Figure 2.1(a)) while those sheet steels that are cold-rolled or cold reduced in thickness are gradual yielding (Figure 2.1(b)).

Sharp yielding steels typically exhibit an upper and lower yield point (points A and B in Figure 2.1(a), respectively). Because the upper yield point is much more sensitive to strain rate, specimen alignment, and shape of the tested cross-section than the lower yield point, the lower yield point is customarily used to represent the yield stress of sharp yielding sheet steels subject to static loading.\(^{25,26} \)
In view of the fact that gradual yielding steels do not have such an obvious yield point, their yield strength is defined by either an offset method or the strain-under-load method as described in ASTM Standard A370. The offset method consists of drawing a straight line parallel to the initial linear portion of the f-ε curve at a given strain offset. For this study, an offset of 0.2 percent strain was chosen. Using this method, the intersection of the straight line and the f-ε curve defines the yield strength as shown in Figure 2.2(a). The strain-under-load method defines the yield point as the stress corresponding to some fixed value of strain. The strain usually chosen is 0.5 percent as shown in Figure 2.2(b).

The slope of the linear portion of the f-ε diagram is known as the modulus of elasticity, E. The point beyond which the f-ε curve becomes nonlinear is called the proportional limit (point A in Figure 2.1(b)). For sheet steels, whether they are gradual or sharp yielding, the proportional limit may be determined by the 0.01 percent offset method in exactly the same manner that the yield stress was defined for gradual yielding sheet steels, except that the offset is now only 0.01 percent.

Once the specimen is strained beyond the yield point, the load carrying capacity of the steel continues to increase slightly in spite of the fact that the cross-sectional area of the specimen is continually decreasing. Since engineering stress is calculated based on the original area, there must be some other phenomenon occurring that causes the increase in load carrying capacity. This phenomenon is commonly referred to as work hardening or strain hardening and may be explained by dislocation theory. The rate of strain hardening is high at the onset of
yielding. However, as the strain is increased, the amount of strain hardening decreases to the point where it can no longer offset the continuous reduction of specimen area. At that point the maximum possible stress or ultimate strength, \( F_u \), is reached in the steel. Further elongation of the tensile specimen results in localized straining of a small portion of the gage length known as necking. The necked region continues to decrease in area at a faster pace than the strain hardening can keep up with which results in a decrease in the total load that the specimen can withstand. This unloading results in all areas of the specimen, other than the necked region, being unloaded back into the elastic range while the stress in the necked area continues to increase until fracture.

A material property that is dependent on the strain that a material can withstand up until fracture is ductility. Ductility is commonly defined by two methods. They are

\[
a) \quad \text{total elongation (percent)} = 100 \times \frac{\ell_f - \ell_o}{\ell_o}, \quad \text{and} \\
b) \quad \text{reduction in area (percent)} = 100 \times \frac{A_o - A_f}{A_o}
\]

In the above equations, the \( f \) subscripts denote the values at fracture. Although standard values are usually used for \( \ell_o \) and \( A_o \), it is important to realize that either method of measuring ductility will give varying results if non-standard values of \( \ell_o \) and \( A_o \) are used.

Another important material property yet to be discussed is the capability of a material to absorb energy without fracture. Energy absorption is especially important in the design of structures such as automobile components, highway guard rails, and machinery guards. For a particular material the energy absorption is given by the area under
the stress-strain curve from zero loading to fracture. Therefore the amount of absorption depends not only on the yield and ultimate strength but on the total elongation of the material as well.

Figure 2.3 illustrates the effect on the stress-strain curve of stressing a given sheet steel beyond the yield stress and then removing the load before failure. As shown by curve 2 of Figure 2.3, if the load is removed at point C along the stress-strain curve, then the unloading path follows a line very nearly the slope of the elastic portion of the stress-strain diagram. The elastic strain, $\varepsilon_e$, recovered upon unloading from point C is equal to the stress at C, $f_c$, divided by the modulus of elasticity, $E$, or $\varepsilon_e = f_c / E$. The permanent set or plastic strain, $\varepsilon_p$, is represented by the line AD. Curve 3 represents the stress-strain curve if reloading occurs immediately and Curve 4 if reloading occurs after strain aging. It can be seen that, if the material is immediately reloaded (Curve 3), strain hardening produces an increase in apparent yield strength and a decrease in ductility as compared to the virgin material. If reloading occurs after a period of time, a phenomenon known as strain aging occurs (Curve 4) which results in an even higher value of yield stress and tensile strength; however, the ductility decreases even more.

If the reloading from point D is opposite the original loading (e.g. compression instead of tension) as shown in Figure 2.4, the new value of the yield point G might be lower than the original yield point B. Also, if this load is reversed so that the load is now in the original direction, the yield point H may be lower than the original yield point B. This
effect was observed by Johann Bauschinger, of Germany, in 1886 and is commonly referred to as Bauschinger Effect 28.

2. True Stress-Strain Curves. The exact or true stress, \( \sigma \), in a tensile test is equal to the load, \( P \), divided by the actual area, \( A \), as follows:

\[
\sigma = \frac{P}{A}
\]  \hspace{1cm} (2.5)

As the load increases and thus the cross-sectional area decreases, the corresponding true stress will be greater than the engineering stress computed for the same loading. Since there is no appreciable change in area in the elastic range, the true and engineering stresses are practically identical. However, as the stress reaches the inelastic range, the strain increases and thus the area decreases much more for a given stress increase than in elastic range. Therefore, the difference between true and engineering stresses become apparent in the inelastic range as can be seen in Figure 2.5. By comparing the shape of the true and engineering stress-strain diagrams in the inelastic range, it can be seen that the difference between the two curves continually increases with increasing strain. It is also interesting to note that the true stress steadily increases up to fracture. This type of continuous increase of the \( \sigma-\epsilon \) curve seems much more logical than the engineering curve because it is difficult to imagine the stress actually decreasing in a material that is tested from zero load to fracture.

The true stress and strain may be related to the engineering stress and strain by assuming constancy of volume of the specimen. In other words, the initial volume, \( A_0 \), should be equal to the instantaneous volume, \( A_t \). Thus
\[ A_0 \ell_0 = A \ell \]  
\[ A = A_0 \ell_0 / \ell = A_0 \left( \frac{\ell}{\ell_0} (1+\epsilon) \right) \]  
\[ A = A_0 / (1+\epsilon) \]  

Therefore the true stress, \( \sigma \), may be given as

\[ \sigma = \frac{P}{A} = \frac{P}{A_0} (1+\epsilon) = f(1+\epsilon). \]  

The true or natural strain, \( \epsilon' \), can be determined from the differential increment of strain, \( d\epsilon' \), as

\[ d\epsilon' = \frac{d\ell}{\ell} \]  

where \( \ell \) is the actual length to which \( d\ell \) is added. The total unit elongation becomes

\[ \epsilon' = \int_{\ell_0}^{\ell} \frac{d\ell}{\ell} = \ln\left(\frac{\ell}{\ell_0}\right) = \ln(1+\epsilon) \]  

Equations 2.8 and 2.10 obviously may be used in converting from engineering stress and strain to true stress and strain\(^{26}\). After necking, the above equations are not valid. Since the length changes within the gage length are now localized in the necked region, the engineering strain, which assumes a uniform strain over the gage length, cannot be used to calculate the true stress and natural strain. An alternate method for computing the true stress in the necked region is described by Hosford and Caddel on page 53 of Ref. 25.

From inspecting the above equations for stress and strain, it can be seen that for very small strains, such as those occurring in the elastic range, the engineering and true stresses and strains will be practically the same. Therefore, for properties such as yield stress and modulus of elasticity, the engineering values should be sufficiently accurate. How-
ever, for studies using stress-strain data in the plastic range, "the true stress and strain are more meaningful than engineering stress and strain." 

B. STRAIN RATE

Strain rate ($\varepsilon'$) is the rate of change of strain ($\varepsilon$) with respect to time ($t$):

$$\varepsilon' = \frac{d\varepsilon}{dt} \quad (2.11)$$

where $\varepsilon$ can be either the engineering or the true strain. For a constant strain rate experiment, the strain rate is simply the total strain divided by the duration of the test:

$$\varepsilon' = \frac{\varepsilon}{t} \quad (2.12)$$

The unit of strain rate is the inverse of time sec$^{-1}$.

For the design of economical and safer cars, understanding of the effects of impact loading, controlled crush and energy absorption on automobile components is essential. Since these design considerations involve dynamic loading, the effects of strain rates on the mechanical properties of the sheet steels must be known in order for the engineer to design a safe and efficient vehicle and moreover to reduce the need for conducting expensive full-scale dynamic testing.

1. Strain Rate Dynamic Testing. Some considerations in strain rate dynamic testing have been summarized by Lindholm as shown in Table 2.1. At strain rates of the order of $10^{-6}$ to $10^{-5}$ sec$^{-1}$ the creep behavior of a material is the primary consideration, usually at elevated temperature for metals, for which the creep-type laws are used to describe the mechanical behavior. At a higher strain rate, in the range of $10^{-4}$ to $10^{-3}$ sec$^{-1}$, the uniaxial tension, compression, or quasistatic
stress-strain curve obtained from constant strain-rate test is used to
describe the material behavior. Although the quasistatic stress-strain
curve is often treated as an inherent property of a material, it is a
valid description of the material only at the strain rate at which the
test was conducted. When higher strain rates are encountered, the stress-
strain relationships may change, and alternate testing techniques have
to be employed. Constant strain-rate tests can be performed with spe-
cialized testing apparatus at strain rates up to approximately \(10^4\)
sec\(^{-1}\). The range of strain rates from \(10^{-1}\) to \(10^2\) sec\(^{-1}\) is generally re-
ferred to as the intermediate or medium strain-rate condition. It is
within this condition that strain-rate effects first become a consider-
ation in most metals, although the magnitude of such effects may be quite
small or even nonexistent in some cases\(^{31}\). Strain rates of \(10^3\) sec\(^{-1}\) or
higher are generally treated as the range of high strain-rate response,
although there are no precise definitions as to strain-rate conditions
and care must be taken in evaluating the test data to note the actual
strain rates rather than the terminology. It is within the high strain-
rate condition that inertia and wave-propagation effects first become
important in interpreting experimental data. At these high rates, care
must be taken to distinguish between average values of stress and strain
and local values that may be the result of one or more high-intensity
stress wave propagation through a material. At the strain rate of \(10^5\)
sec\(^{-1}\) or higher, it is generally dealing with shock waves propagating
through materials that are in a state of uniaxial strain. At these very
high rates and the associated very short time scale involved,
thermodynamic considerations become important\(^{31}\). Table 2.2\(^{32}\) shows the
experimental techniques that are used for various strain rate conditions in compression, tension, and shear testing. Unfortunately, there are no standardized procedures for high strain rate tests. Many different machines, specimen configurations, and measuring devices have been used. This makes a comparison of the test results of different investigators difficult and often makes it impossible to compare the properties of a group of materials since the behavior of a material is quite often influenced by the experimental conditions. It is important that the true behavior be studied by different methods to isolate any excessive influence of the technique and to verify the validity of the data.

2. Effect of Strain Rate on Mechanical Properties. The effect of strain rate on mechanical properties varies for each material. These general trends are well known, but because the magnitude of the change in properties with strain rate is so varied for each material, no general quantitative theory exists that satisfactorily predicts the mechanical behavior of materials over a wide range.

For most materials, mechanical properties tend to increase at higher strain rates. The following sections discuss the effect of strain rate on mechanical properties of structural and high strength sheet steels, stainless steels, and aluminum.

a. Structural Steels and High Strength Steels. The effect of the strain rate on the mechanical behavior of mild steel has long been a subject of interest to researchers since the beginning of this century. Figure 2.6 shows stress-strain curves obtained from structural steels tested at various strain rates. Clearly, the yield strength of the mate-
rial increases as the strain rate increases. This is the most consistently observed effect of strain rate on material properties.

Historically, Ludwik was the first to study the effect of the speed of stretching upon the stress at which a metal yields. He found a logarithmic relation between the stress at which a metal yields and the strain rate as early as 1909.

In 1925, Korber and Storp compared impact tests with ordinary static tests for various metals. These tests showed a considerable increase in the yield stress in the more rapid tests.

The effect of changing the speed of deformation on various metals were studied by Prandtl and his associates in 1932. Their results were in agreement with the relation found by Ludwik.

In 1937, Winlock and Leiter investigated the effect of the strain rate upon the yielding of deep-drawing sheet steel. Their results showed that the yield stress and the corresponding elongation were considerably affected by the strain rate. The ultimate strength was also influenced but to a smaller extent than the yield strength.

In the 1940s, Manjoine studied the relationships between strain rate, temperature, and the material properties of mild steels. Figure 2.7 illustrates the true yield stresses at various strains for a low-carbon steel at room temperature. It can be seen that between strain rates of $10^{-6}$ sec$^{-1}$ and $10^{-3}$ sec$^{-1}$ yield stress increases only by 10%. Above the strain rate of 1.0 sec$^{-1}$, however, the same increase of strain rate doubles the yield stress. For the data shown in Figure 2.7, at every level of strain, the flow stress increases with increasing strain rate. However, a decrease in strain-hardening rate is exhibited at higher strain rate.
The results of the combined effects of strain rate and temperature at 200, 400, and 600°C are shown in Figures 2.8 to 2.10, respectively. At the highest temperature of 600°C, yield strength increases with increasing strain-rate, but strain hardening increases (rather than decreases) with increasing strain rate. At intermediate temperatures shown in Figures 2.8 and 2.9, however, regions of negative strain rate sensitivity are visible; that is, under certain conditions of strain, strain rate, and temperature, the flow stresses of carbon steels decrease with an increase in strain rate. This is in contrast with the usual strain rate effect.

In 1963, United States Steel Corporation conducted numerous tests on high-strength, low-alloy steels (COR-TEN and TRI-TEN) for the purpose of studying the effects of the strain rate and temperature on the tensile properties of these steels. The tests were conducted at strain rates of $3 \times 10^{-5}$ in./in./sec, $5 \times 10^{-3}$ in./in./sec, and 1.0 in./in./sec at temperature of -50°F, 75°F (room temperature), and 600°F. The results obtained from this investigation indicated that as the strain rate was increased at -50°F and at 75°F, the tensile strength and the 0.2 percent offset yield strength increased as shown in Figures 2.11 and 2.12. However, as the strain rate increased at 600°F, the tensile strength decreased. The ductility of the COR-TEN steel, as measured by percent elongation and reduction of area, did not appear to be strain-rate sensitive at -50°F and room temperature, but at 600°F, the reduction of area for the fastest rate was higher than that for the slowest rate. The percent elongation of the TRI-TEN steel appeared to be somewhat strain-rate dependent, decreasing slightly as the strain rate increased.
In 1974, Chatfield and Rote40 completed a comprehensive report concerning the influence of strain rate on the mechanical properties of high strength, low alloy (HSLA) steels. In this study six different HSLA steels were tested with yield strengths ranging from 40 to 80 ksi. They also tested three different aluminum alloys for comparison with the HSLA steels. Approximate strain rates used were 0.008, 0.8, 8.0 and 80. in./in./sec. All tests were performed at room temperature. Figure 2.1340 shows the relationship between yield and tensile strengths, uniform elongation and strain rate for a typical HSLA steel.

As can be seen from Figure 2.13, the yield and tensile strengths both increase substantially with increasing strain rate while the uniform elongation, which is the strain at the onset of the necking, decreases slightly. This indicates that the total elongation is relatively independent of strain rate. It is, therefore, expected that the absorbed energy of the HSLA steel also increases with increasing strain rates. Such an increase in absorbed energy is obviously desirable for the automotive components.

Based on the research findings presented in Refs. 25 and 40, the true stress in metals may be determined by the strain rate as follows:

\[ \sigma = C \varepsilon^m \]  

(2.13)

where

\( \sigma \) = true stress

\( \varepsilon' \) = true strain rate

\( m \) = strain rate sensitivity exponent

\( C \) = material constant
In Equation (2.13), it is possible to determine the value of "m" from tensile tests by changing the strain rate suddenly and by measuring the instantaneous change in stress. This technique is illustrated in Figure 2.14. By applying Equation (2.13) to two different strain rates and eliminating C, we have

\[ m = \frac{\ln(\sigma_2 / \sigma_1)}{\ln(\dot{\varepsilon}_2 / \dot{\varepsilon}_1)} \]  

(2.14)

According to Hosford and Caddel, the magnitude of "m" for most metals is usually between 0 and 0.03. The value of C depends on the strain rate, temperature and the type of material. For a given material, the values of C and m can be determined empirically. For example, the resulting magnitudes of C and m obtained from Chatfield and Rote's tests are listed in Table 2.3. It is interesting to note from Table 2.3 that the m values range from 0.018 to 0.056, which are slightly exceeding the range of m values given by Hosford. As expected, the values of lnC (and thus C) increase as the yield strength increases. However, the m values show a steady decrease with the increasing yield strength. An analysis of the results given in Table 4 of Chatfield and Rote's report seems to indicate that the increase in C is offset by the decrease in m values, such that the total increase in yield strength for a given strain rate remains approximately the same regardless of the material strength.

Another useful relationship between the true stress and strain rate is given by Hosford as:

\[ \sigma_2 = \sigma_1 \times (\dot{\varepsilon}_2 / \dot{\varepsilon}_1)^m \]  

(2.15)

where \( \sigma_1 \) and \( \sigma_2 \) are the true stresses corresponding to strain rate \( \dot{\varepsilon}_1 \) and \( \dot{\varepsilon}_2 \), respectively. Therefore, if \( \sigma_1 \), \( \dot{\varepsilon}_1 \) and m are known, then \( \sigma_2 \) can be found for any desired value of \( \dot{\varepsilon}_2 \).
If the strain rate sensitivity of a material is known as a design parameter, the engineer may use this property to his advantage and thus a more economical design may be obtained. For example, an automotive engineer may take advantage of the increased yield point (if available) caused by the high strain rate associated with impact when he designs a part to withstand impact loading without permanent deformation.

In 1982, Watanabe studied the yield behavior of low-carbon sheet steels at room temperature under the strain rates of $10^{-4}$ to $10^{-1}$ sec$^{-1}$ using an Instron type machine. The results showed another break point of the dependence of the yield stress on the strain rate of $3 \times 10^{-3}$ sec$^{-1}$, which is different from Manjoine's strain rate of $10^{-1}$ sec$^{-1}$ as shown in Figure 2.15. This means that the dependence of yield stress, yield point elongation, and tensile strength on the strain rate in the range of high strain rate above $3 \times 10^{-3}$ sec$^{-1}$ is larger than that at lower strain rates. Figure 2.15 also shows that the yield stress is more sensitive to strain rate as compared with the tensile strength.

Also in 1982, Peterson, Schwabe, and Fertis conducted experiments to measure the effect of strain rate on the tensile properties of SA-106 carbon steel pipe. It was observed that the increase in the strain rate from $4 \times 10^{-4}$ to 4 sec$^{-1}$ raised the yield strength by approximately 30 percent as illustrated in Figure 2.16.

In 1983, Sachdev and Wagoner found that the strain rate sensitivity is strongly dependent on the strain rate for steel. This investigation included four types of steels: an interstitial free (IF) steel, a hot rolled, plain carbon steel (HR), and two high strength steels one with a ferrite-pearlite microstructure (HSLA) and the other with a ferrite-
martensite (DP) microstructure. A new equation was developed to correlate the strain-rate sensitivity and the strain rate as follows:

$$m = b \varepsilon^n$$

(2.16)

In the above equation, $a$ and $b$ are constants to be determined from tests. Figure 2.17 shows the strain-rate sensitivity index, $m$, for the steels tested as a function of strain rate. The curves represent the best fits for Equation (2.16) for the steels tested under the selected strain rate range. The best fit coefficients obtained from these curves are given in Table 2.4 along with the $m$-values. Note that for each steel the strain-rate sensitivity is well-characterized by the new equation.

In 1984, Meyer conducted tension tests on high strength sheet steels at strain rates between $5 \times 10^{-4}$ sec$^{-1}$ and $5 \times 10^3$ sec$^{-1}$. Figure 2.18 shows the stress-strain curves of the tested steel at different strain rates. It is observed from this figure that both yield and ultimate tensile strengths are increased with the increasing strain rate. However, the ductility decreased when the strain rate increased from $5 \times 10^{-4}$ sec$^{-1}$ to $2 \times 10^3$ sec$^{-1}$. At higher strain rates above $2 \times 10^3$ sec$^{-1}$, the material becomes more ductile again.

Recently, Nagorka conducted an experimental investigation to observe the effect of microstructure and strain rate on the stage III strain hardening and ductility of dual-phase steels. Five types of steels included in this investigation were cold-rolled, normalized, martensitic, tempered martensitic, and ferrite-carbide. Table 2.5 lists the values of the strain rate sensitivity for the five steels studied. The $m$ values were calculated for low to intermediate strain rates ($6.7 \times 10^{-5}$ to $6.7 \times 10^{-4}$ sec$^{-1}$) and intermediate to high strain rates ($6.7 \times 10^{-4}$...
sec\(^{-1}\) to 6.7 \times 10^{-3}\) sec\(^{-1}\). Based on the \(m\) values given in this table, Nagorka concluded that the strain rate sensitivities of various microstructures are the same for any given strain rate and increase with increasing strain rate. These observations indicate that \(m\) is insensitive to changes in microstructures. Also, it was concluded from this study that the uniform elongation increases slightly with increasing strain rate for most of the microstructures tested, whereas post-uniform elongation increases significantly with increasing strain rate.

Another very important mechanical property is the modulus of elasticity, \(E\). Norris et al. state in Ref. 34 that, based on a limited number of tests on ordinary structural carbon steel, the modulus of elasticity is unaffected by strain rates.

b. Stainless Steels. Albertini and Montagnani\(^{47}\) have conducted tests on three austenitic stainless steels (AISI Types 304, 304L, and 347). The results of these tests are presented in Figures 2.19 to 2.21\(^{47}\), which indicate an increase in yield and ultimate strengths for all materials when the strain rate increases. However, decreases in the total elongations are exhibited.

In 1984, Hopkinson split-bar tests were performed on Type 21-6-9 austenitic stainless steels from ambient temperature to 1023 K by Kassner and Breithaupt\(^{48}\). These high-strain-rate tests (\(10^2\) to \(10^4\) sec\(^{-1}\)) were compared with lower-strain-rate tests (\(10^{-4}\) sec\(^{-1}\)). The results as shown in Figure 2.22\(^{48}\) indicate that the strain-rate sensitivity of this type of stainless steel is not strongly dependent on the strain rate. The value of \(m\) was determined to be 0.03846 by measuring the slope of the indicated best-fit line.
c. **Aluminum.** Structural aluminums were found to be less strain rate sensitive than steels. Figure 2.23 shows the data obtained for 1060-0 aluminum. Between strain rates of $10^{-3}$ sec$^{-1}$ and $10^3$ sec$^{-1}$, the stress at 2% plastic strain increases by less than 20%. Another contrast to the behavior of steel as demonstrated in Fig. 2.23 is that strain hardening increases with increasing strain rate. Reference 50 summarizes several data sets relating to the yield stress dependence on strain rate in steel and aluminum (Figures 2.24 and 2.25). The comparison shows that for aluminum, the effect on yield stress is less significant and occurs only at extremely high strain rates. Note the difference in vertical scales in Figs. 2.24 and 2.25.

A large amount of the available data has been reviewed by Lindholm and Bessy. The materials tested include several commercial aluminum alloys. The data cover strain rates from $10^{-5}$ to about $10^3$ sec$^{-1}$. The strain rate sensitivity was found to be constant over a large range of strain rates. Figures 2.26 to 2.28 show the effect of plastic strain rate on the flow stress at a constant true strain and a constant temperature. In some cases, rate independent behavior is observed at low strain rates. In general, the value of $m$ was found to increase with increasing strain rate. From these figures, it can be seen that the flow stress may be related to the strain and strain rate over the wide range of strain rates by the following equation:

$$\sigma = \sigma_0 (\varepsilon) + \sigma_1 (\varepsilon) \log \varepsilon$$

(2.17)

where $\sigma_0 (\varepsilon)$ is the stress-strain relation at unit strain rate.

Green and Maiden have conducted two compression tests on two types of aluminums, 6061-T6 and 7075-T6. The range of the strain rates was from...
Figure 2.29 shows the stress strain data of 7075-T6 at various strain rates. It is apparent from the results of these tests that both aluminums are not sensitive to the change in the strain rate.

Figure 2.30 shows a method of comparing the previous investigation data in terms of a rate-sensitivity parameter versus the static flow stress. The parameter is the increase in flow stress from a static test to a dynamic test at a given strain divided by the static flow stress and the log of the difference in strain rates. It represents the percentage increase in stress per unit of log strain rate. It is shown from this figure that the degree of rate sensitivity is increased as material strength is decreased, or as purity increases.

3. Strain-Rate History Effect. 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 number of investigators have examined the loading history to determine its contribution to the mechanical behavior characteristics. A technique that has achieved popularity over the last decade is the jump test or more properly the incremental strain-rate test, for which a specimen is subjected to a slow rate of loading followed by a very high loading rate.

Incremental as well as interrupted (prestrained) tests are most useful tools for the study of strain-rate history effects in metal, especially if the change in strain-rate covers several orders of magnitude, say from quasi-static to dynamic or vice versa, in order to
submit the material in question to the most critical and demanding conditions. The early experiments involved with dynamic strain rates and intended for a study of strain-rate history are those of Lindholm. Figures 2.31 to 2.33 show Lindholm’s results for cyclic loading of aluminum. It is evident that the stress in dynamic tests following a static pre-loading is not equal to the stress found at the same strain in all dynamic loading (as shown by the dotted line). This difference is due to strain rate history. In addition, Lindholm wondered if the result was influenced by the dwell-time at zero load. To investigate this question he loaded a specimen dynamically to 8 percent strain, unloaded, and then reloaded dynamically. The result, as shown in Fig. 2.33, shows a history effect for a dwell-time of three minutes, while for a dwell-time of 450 micro seconds none can be seen.

Sirakashi and Usui tested three materials over a large range of temperatures. Jumps in strain rate were made from $10^{-3}$ sec$^{-1}$ to four different dynamic strain rates. Figures 2.34 and 2.35 show the effect of alteration of strain rate upon the flow stress on the way of straining. In Fig. 2.34, point $A_o$ is reached with a constant strain rate of $10^{-3}$ sec$^{-1}$. The strain rate is then changed to $10^{-3}$ sec$^{-1}$. Two dotted curves in the figure are stress strain curves with a constant strain rate. It may be seen in the figure that the flow stress does not reach the value at point $A_2$, which lies on the dotted curves with constant strain rate of $10^{-3}$ sec$^{-1}$, in spite of the alteration of strain rate. The same situation may be seen in Fig. 2.35, where the strain rate is changed from $10^3$ sec$^{-1}$ to $10^{-3}$ sec$^{-1}$ at point $B_o$. These results clearly show that
the history of strain rate is another factor which has an effect upon the flow stress. In other words, the flow stress will be different depending upon the strain rate history, which the material has experienced, even if strain, strain rate and temperature are all the same at the moment considered. The effect of strain rate history may be attributed to the "memory", of strain rate which has been stored in the material, probably as a change in structure.

The most extensive series of jump tests is probably that of Eleiche and Campbell conducted in 1976. These investigators tested copper, titanium and mild steel. The tests were performed over a range of temperatures and to strains up to 60% in shear. They concluded that copper is sensitive to strain rate history, while titanium and steel are less sensitive to history, but more sensitive to direct effects of strain rate.

Jump tests to higher strain rates using 1020 hot rolled steel and 1080 cold rolled steel were performed by Wilson et al. in 1979. See Figures 2.36 and 2.37. Both steels, 1020 hot rolled steel, and 1080 cold rolled steel show a strong strain rate sensitivity and insensitivity to strain rate history.

A recent experimental study of the strain rate history effect on the tensile strength of AISI type 316 stainless steel using interrupted testing was conducted by Eleiche, Albertini, and Montagnani in 1985. True stress-true strain curves resulting from their interrupted testing accompanied by a strain rate change from 0.004 to 500 sec\(^{-1}\) at various values of strain are presented in Fig. 2.38. Also plotted are curves showing the variation of the temperature rise in each
specimen during the corresponding dynamic deformation. The investigated prestrain range was from 0.0047 in./in to 0.3048 in./in. It can be seen from this figure that a well-defined yield point whose level is much higher than that reached in the quasi-static prestraining. For small prestrains, this yield stress level is very close to the flow stress level reached at the same strain in a test conducted entirely at the dynamic rate (curve B in Fig. 2.38). The conclusion of this study was that even stainless steel is known to be strain-rate sensitive, it has been shown that it is insensitive to strain-rate history, within the range of strain rate covered in the tests and at ambient temperature.
III. EXPERIMENTAL PROGRAM

A. MATERIALS

Currently, numerous grades of high strength sheet steels are commercially available for automotive structural components. Two types of sheet steels (35XF and 50XF) were selected by members of the Task Force on Automotive Structural Design of the AISI Automotive Applications Committee for the purpose of studying the effect of strain rate on the mechanical properties of high strength sheet steels and the structural strength of cold-formed steel members subjected to dynamic loads. The chemical compositions for these two sheet steels are listed in Table 3.1. Also included in this table is the chemical composition of 100XF sheet steel, which was used in the first phase of the study of automotive structural components using high strength sheet steels. The 100XF sheet steel was also used in the study of the effect of strain rate on the mechanical properties.

B. UNIAXIAL TESTS

All these three virgin materials listed in Table 3.1 were uniaxially tested in tension in the longitudinal (parallel to the direction of rolling) and transverse (perpendicular to the direction of rolling) directions under three different strain rates of $10^{-4}$, $10^{-2}$, and 1.0 in./in./sec. Two of the three materials (50XF and 35XF) were also tested in tension in both directions to determine the combined effects of cold-stretching and strain rate. The amounts of uniform cold-stretching used for the tests were 0.02 in./in. (20 mils) and 0.08 in./in. (80 mils). In order to determine the combined effects of strain rate and aging, half
of the coupons (non-aged coupons) were tested in an average of two days after cold stretching operation. The remaining half of the cold-stretched coupons (aged coupons) were tested to failure under different strain rates at least 30 days after cold stretching operation.

1. **ASTM Specifications.** All tension tests followed the procedures outlined in the ASTM Specifications listed below:

   E8-69    Tension Testing of Metallic Materials
   E83-67   Standard Method of Verification and Classification of Extensometers
   E111-82  Standard Test Method for Young's Modulus, Tangent Modulus and Chord Modulus

2. **Specimens.** The tensile specimens tested in the longitudinal and transverse directions were prepared by the Machine Shop of the Department of Civil Engineering at the University of Missouri-Rolla. The test specimens were cut from the quarter points of the steel sheets as shown in Figure 3.1. The sketch in Figure 3.2 shows the tensile specimen dimensions for the three materials (35XF, 50XF, and 100XF). A total of 124 coupons were tested in this phase of study. They are summarized in the following 22 different cases:

<table>
<thead>
<tr>
<th>Cold-Stretched Condition</th>
<th>Type of Material</th>
<th>Number of Coupons Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal Tension (LT)</td>
<td>100XF-LT</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>50XF-LT</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>35XF-LT</td>
<td>9</td>
</tr>
<tr>
<td>Transverse Tension (TT)</td>
<td>100XF-TT</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>50XF-TT</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>35XF-TT</td>
<td>6</td>
</tr>
<tr>
<td>Cold-Stretched Condition</td>
<td>Type of Material</td>
<td>Number of Coupons Used</td>
</tr>
<tr>
<td>--------------------------</td>
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<td>------------------------</td>
</tr>
<tr>
<td>2% Cold-Stretched</td>
<td></td>
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</tr>
<tr>
<td>Non-Aged Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal Tension</td>
<td>50XF-LT</td>
<td>6</td>
</tr>
<tr>
<td>(LT)</td>
<td>35XF-LT</td>
<td>6</td>
</tr>
<tr>
<td>Transverse Tension</td>
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<td>2</td>
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<td>(TT)</td>
<td>35XF-TT</td>
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<tr>
<td>8% Cold-Stretched</td>
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<td>Non-Aged Materials</td>
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<tr>
<td>Longitudinal Tension</td>
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<tr>
<td>(LT)</td>
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<tr>
<td>Transverse Tension</td>
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<tr>
<td>(TT)</td>
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<tr>
<td>2% Cold-Stretched</td>
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<td>Aged Materials</td>
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<tr>
<td>Longitudinal Tension</td>
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</tr>
<tr>
<td>(LT)</td>
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<tr>
<td>Transverse Tension</td>
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</tr>
<tr>
<td>(TT)</td>
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<tr>
<td>8% Cold-Stretched</td>
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<tr>
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<tr>
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<td>4</td>
</tr>
<tr>
<td>(TT)</td>
<td>35XF-TT</td>
<td>4</td>
</tr>
</tbody>
</table>

3. **Equipment.** All the specimens were tested in a 110 kips MTS 880 Test System located in the UMR Engineering Research Laboratory. Figure 3.3 shows the Test System along with the remaining equipment used for the tension tests under controlled strain rates. Other equipment used for the tests includes the MTS controller (Fig. 3.4), the data acquisition
system (Fig. 3.5), Data General graphic monitor (Fig. 3.6), Data General
MV-10000 mini computer to store and manipulate the data (Fig. 3.7), MTS
Model No. 732.25b-20 extensometer (Figs. 3.8a and 3.8b), and IBM PS/2
Model 30 personal computer with IBM color plotter and NEC Pinwriter P5XL
printer (Fig. 3.9).

An MTS extensometer with a 2-in. gage length was used to measure the
strains from zero load to failure. The classification of this extensometer
according to ASTM Designation E-83 was found to be dependent on the
extensometer range used in the tests. Table 3.2 contains the classifi­
cations of the four extensometer ranges according to the MTS transducer
calibration data.

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 Standard.

Figure 3.10 shows the MTS 880 automated test system which consists
of four components: the load frame, the control console, the CAMAC (Com­
puter Automated Measurement and Control) data acquisition, and Data Gen­
eral MV-10000 computer. The testing machine is of a servohydraulic
closed-loop type. Figure 3.11 shows the simplified block diagram of the
servo control loop. The moving piston is driven by a double-action hy­
draulic cylinder; so that it can operate under tension and compression.

The fluid pressure in the chamber is controlled by a servovalve. This
servovalve responds to the difference between the measured signal and
the desired signal. The signal is amplified to drive the valve so as to
remove the error. There are three main modes of operating the machine,
commonly referred to as stroke, strain, and load. Under the stroke mode,
the movement of the piston is the controlling variable. Under the load mode, it is the load acting on the specimen. Under the strain mode, it is the strain, as read from the extensometer. For each of these three modes, different time functions can be established by the function generator to match the application needed. Tensile tests under a constant strain rate can be made by setting a ramp function under the strain mode. The slope of this ramp is the desired strain rate. Each of these modes has four different ranges of operation i.e., 100%, 50%, 20%, and 10%. Table 3.3 summarizes the transducer ranges and the corresponding load, strain, or displacement values. The test results can be processed by the Data General mini computer and displayed graphically as desired. The data acquisition used in this system conforms to the CAMAC standards. The main data acquisition module used in this system is a Kinetic Systems Model 4022 Transient Recorder. The unit has 32 simultaneous sampling input channels at a resolution of 12 bits. The unit is capable of acquiring sets of data at the maximum rate of 25,000 sets of readings per second. The recorder has a storage capacity of 1,000,000 samples. The simultaneous sampling feature of the system eliminates the timing skew between data points. After the data has been acquired, it is downloaded into the computer 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.

4. Procedure. Prior to testing, the dimensions of the tensile specimens were measured to the nearest 0.001 in., cleaned with acetone, and the gage length (2 in.) was marked in ink. The grips of the machine were aligned by operating the machine under stroke mode. The specimen was
then placed in the grips such that the longitudinal axis of the specimen coincided with the center line of the grips. The load mode was selected to place the specimen in the grips before running the test. Next, the extensometer was attached to the specimen such that the extensometer knife edges lined up with the gage marks as illustrated in Figure 3.8. The function generator was then programmed to produce the desired ramp. The ramp function has two time values needed to be selected i.e., ramp time 1 (RT1) and ramp time 2 (RT2). See Fig. 3.12. Table 3.4 shows ramp time 1 and the corresponding strain-rate value. Ramp time 2 was chosen to give enough time to remove the extensometer and the specimen from the load frame. Transfer from load mode to strain mode was made before the test was started. For almost all the tests, load range 4, strain range 1, and stroke range 1 were selected. As the test proceeded, the stress-strain graph was plotted simultaneously on the graphic display terminal. The stress and strain data were stored by the Data General computer for later plotting and determination of mechanical properties.

A constant strain-rate is very difficult to maintain with the conventional testing machine especially at the high strain rate. The strain rate was controlled electronically by the new MTS 880 Test System, which allowed the exact strain rates to be performed without any difficulty. Figures 3.13 to 3.15 show the strain versus time curves for different strain rates.

The cold-stretching coupons were loaded to the desired 2% strain or 8% strain by using strain as a control mode with the strain rate of 0.1 in./in./sec. The span in the MTS system controller was used to stop the test when the desired strain is reached.
C. RESULTS

1. Stress-Strain Curves. 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. Because the stresses were computed by dividing the loads by the original cross-sectional areas of the specimens, they should be regarded as the engineering stress-strain curves. Figures 3.16 through 3.37 present the stress-strain curves for the following 22 different cases, which were studied under different strain rates (0.0001, 0.01, and 1.0 in./in./sec.).

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<th>Cold-Stretched Condition</th>
<th>Type of Material</th>
<th>Figure Number</th>
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</tr>
<tr>
<td>Longitudinal Tension (LT)</td>
<td>50XF-LT</td>
<td>3.26</td>
</tr>
<tr>
<td></td>
<td>35XF-LT</td>
<td>3.36</td>
</tr>
<tr>
<td>Transverse Tension (TT)</td>
<td>50XF-TT</td>
<td>3.27</td>
</tr>
<tr>
<td></td>
<td>35XF-TT</td>
<td>3.37</td>
</tr>
</tbody>
</table>

For the purpose of comparison, each figure includes two or three stress-strain curves representing the test data obtained from the same material for different strain rates. In order to study the effect of aging on the mechanical properties of 50XF-LT steel, Figures 3.59 to 3.61 compare three stress-strain curves for 50XF-LT steel with different amount of cold stretching tested under a constant strain rate.

2. Mechanical Properties. The procedures used for determining the mechanical properties of sheet steels are discussed in the subsequent sections (Sections III.C.2.a through III.C.2.c). The mechanical properties so determined are the yield point $F_y$, the tensile strength $F_u$, and
elongation in 2-in. gage length. These tested mechanical properties are presented in Tables 3.5 through 3.15 for each individual test. Tables 3.16 through 3.21 present the average values of the mechanical properties for each material tested in either longitudinal tension (LT) or transverse tension (TT), but with different amount of cold stretching (i.e., virgin material, 2%, or 8%) under different strain rates (0.0001, 0.01, or 1.0 in./in./sec.).

a. Yield Strength or Yield Point, $F_y$. The method commonly used to determine the yield point of sheet steels depends on whether the stress-strain curve is of the gradual or sharp-yielding type. For the types of sheet steels tested in this phase of study, the stress-strain curves of the 100XF and 50XF sheet steels are the sharp-yielding type, while the stress-strain curves of the 35XF steel are the gradual-yielding type. Because the 50XF sheet steel exhibited a considerable amount of strain hardening, the stress-strain curves became the gradual-yielding type after the material was cold-stretched to a selected strain of either 2% or 8%.

The yield point of the sharp-yielding steel was determined as the stress where the stress-strain curve becomes horizontal. Typical sharp yielding stress-strain curves are shown in Figure 3.16 for the 100XF steel in the longitudinal direction. For this case, the lower yield point is given in Table 3.5. The same method was used to determine the yield points included in Table 3.6 for the 50XF sheet steel.

For the gradual-yielding type stress-strain curves as shown in Figure 3.28, the yield point of 35XF steel was determined by the intersection of the stress-strain curve and the straight line drawn parallel to the
elastic portion of the stress-strain curve at an offset of 0.002 in./in. A Fortran 77 code was written to determine the yield points presented in Tables 3.7 through 3.15 for the gradual-yielding type curves using the Least Square Method.

b. Ultimate Tensile Strength, $F_u$. The ultimate tensile strength was determined from each of the tension tests as the maximum stress that the given tensile coupon could withstand before fracture. This value was calculated by the computer for each test and is presented in Tables 3.5 through 3.15.

c. Ductility. Ductility is a very important property of high strength sheet steels not only for the structural behavior of the member, but also for the fabrication of the desired structural shape. In this study, ductility was determined by the total elongation in a 2-in. gage length. For this method, the maximum strain recorded by the computer before fracture was taken as the ductility. The maximum elongation was also verified by placing the fractured ends of the specimen together and measuring the distance between the gage marks.

D. DISCUSSION

The test results presented in Section III.C are discussed in this section with an emphasis on the effects of strain rate on the mechanical properties of sheet steels. The materials used in this experimental program included virgin steels and steels with different amount of cold stretching. They were tested in both longitudinal tension and transverse tension.

1. Mechanical Properties. The test results indicate that all mechanical properties are affected by the strain rate and the amount of cold
stretching. Table 3.22 compares 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 yield stress and tensile strength are discussed in the following sections.

a. Yield Strength or Yield Point, $F_y$. In Table 3.22, 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 above expressions, $(F_y)_d$ is the yield strength determined for the strain rate of 1.0 in./in./sec. while $(F_y)_s$ is the yield strength determined for the strain rate of 0.0001 in./in./sec. 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 this investigation are: 4% for 100XF steel, 4% to 15% for 50XF steel, and 12% to 29% for 35XF steel when the strain rate increased from 0.0001 to 1.0 in./in./sec. It is observed from this table that the increases in yield strength for the virgin materials are independent of the test direction (LT or TT). 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 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. In addition, Figs. 3.24 to 3.27 show that the strain aging has little or no effect on the type of stress-strain curve.

b. Ultimate Tensile Strength, $F_u$. 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 this investigation are: 4% for 100XF steel, 7% to 11% for 50XF steel, and 13% to 18% for 35XF steel when the strain rate increased from 0.0001 to 1.0 in./in./sec. It is noted from Table 3.22 that the amounts of increase in ultimate tensile strength due to the increase in strain rate are approximately the same for both longitudinal tension and transverse tension.

2. Strain Rate Sensitivity. In the literature review the strain rate sensitivity was discussed in Section II.B.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 as

\[
m = \ln\left(\frac{\sigma_2}{\sigma_1}\right) / \ln\left(\frac{\varepsilon_2'}{\varepsilon_1'}\right)
\]

Figures 3.38 through 3.58 compare the average values of the yield and ultimate tensile strengths at different strain rates for different cases. The data plotted in these figures are in terms of flow stress vs. strain rate on a logarithmic scale. The slopes of the straight lines shown in these figures represent the material strain rate sensitivity values, which were calculated on the basis of the above equation and are listed in Table 3.23 for different cases. The value of \( m_1 \) was calculated for the yield strengths corresponding to the strain rates of 0.0001 in./in./sec. and 0.01 in./in./sec., while the value of \( m_2 \) was calculated for the yield strengths corresponding to the strain rates of 0.01 in./in./sec. and 1.0 in./in./sec. 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 in./in./sec. and 1.0 in./in./sec. From Table 3.23, it can be seen that, in general, the value
of $m$ increases as the strain rate increases. The strain rate sensitivity decreases progressively as the static yield strength level or the amount of cold stretching increases.
IV. CONCLUSIONS

In the past, high strength sheet steels with various yield strengths up to 190 ksi have been used for auto parts and structural components for the purpose of achieving fuel economy. In order to provide some technical assistance for the design of automotive structural components using high strength sheet steels, American Iron and Steel Institute published the first edition of the "Guide for Preliminary Design of Sheet Steel Automotive Structural Components" in 1981 and the first edition of the "Automotive Steel Design Manual" in 1986. The latter brings together material properties, product design, and manufacturing information to make the most effective use of sheet steels with yield strengths of up to 140 ksi.

In view of the fact that the available design equations were developed on the basis of previous tests subject to static loads and that the yield strength, tensile strength, and the stress-strain relationship of sheet steels are affected by the strain rate used for the tests, additional research work was conducted at the University of Missouri-Rolla since May 1988. The objective of the work is to study the effect of strain rate on the mechanical properties of the selected sheet steels and the structural strengths of the cold-formed steel members when they are subjected to dynamic loads. The major task is to develop the needed background information for improvement of the existing design procedures.

During the period from May 1988 through December 1988, progress has been made on a study of the effect of strain rate on mechanical properties of sheet steels. This initial work included a review of literature and
testing of 124 tension specimens. The literature survey is presented in Section II. Section III contains the detailed information on the experimental investigation, which includes materials, test specimens, equipment, test procedure, test results and the discussion of test data.

Future research work will include the testing of compression coupons and a study of the structural strengths of cold-formed steel stub columns and beams subject to dynamic loads. Additional evaluation of the test data on tensile coupons will be presented in the Twelfth Progress Report.
ACKNOWLEDGMENTS

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REFERENCES

1. American Iron and Steel Institute, "Cost-Effective Weight Reduction with Sheet Steel", SG-631R.


3. American Iron and Steel Institute, "High Strength Sheet Steel Source Guide", SG-603D.


Table 2.1 Dynamic Aspects of Mechanical Testing

<table>
<thead>
<tr>
<th>Characteristic time (sec)</th>
<th>10^6</th>
<th>10^4</th>
<th>10^2</th>
<th>10^{-2}</th>
<th>10^{-4}</th>
<th>10^{-6}</th>
<th>10^{-8}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain rate (sec^{-1})</td>
<td>0</td>
<td>10^{-6}</td>
<td>10^{-4}</td>
<td>10^{-2}</td>
<td>10^2</td>
<td>10^4</td>
<td>10^6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method</th>
<th>Usual method of loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep</td>
<td>Constant load or stress machine</td>
</tr>
<tr>
<td>Quasistatic</td>
<td>Hydraulic or screw machine</td>
</tr>
<tr>
<td>Intermediate Strain-rate</td>
<td>Mechanical or explosive impact</td>
</tr>
<tr>
<td>Bar impact</td>
<td>Light-gas gun or explosive driven plate impact</td>
</tr>
<tr>
<td>High-velocity plate impact</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Condition</th>
<th>Dynamic considerations in testing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isothermal</td>
<td>Constant strain-rate test</td>
</tr>
<tr>
<td>Adiabatic</td>
<td>Mechanical resonance in specimen and machine</td>
</tr>
<tr>
<td>Increasing stress levels</td>
<td>Elastic-plastic wave propagation</td>
</tr>
<tr>
<td>Plane stress</td>
<td>Shock-wave propagation</td>
</tr>
<tr>
<td>Plane strain</td>
<td></td>
</tr>
</tbody>
</table>

Inertia forces neglected
Inertia forces important
Table 2.2 Experimental Techniques for High Strain Rate Testing

<table>
<thead>
<tr>
<th>Mode</th>
<th>Applicable Strain Rate, sec⁻¹</th>
<th>Testing Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression</td>
<td>≤ 0.1</td>
<td>Conventional load frames</td>
</tr>
<tr>
<td></td>
<td>0.1 to 100</td>
<td>Special servohydraulic frames</td>
</tr>
<tr>
<td></td>
<td>0.1 to 500</td>
<td>Cam plasometer and drop test</td>
</tr>
<tr>
<td></td>
<td>200 to 10⁴</td>
<td>Hopkinson pressure bar</td>
</tr>
<tr>
<td></td>
<td>10⁴ to 10⁵</td>
<td>Taylor impact test</td>
</tr>
<tr>
<td>Tension</td>
<td>≤ 0.1</td>
<td>Conventional load frames</td>
</tr>
<tr>
<td></td>
<td>0.1 to 100</td>
<td>Special servohydraulic frames</td>
</tr>
<tr>
<td></td>
<td>100 to 10⁴</td>
<td>Hopkinson pressure bar</td>
</tr>
<tr>
<td></td>
<td>10⁴</td>
<td>Expanding ring</td>
</tr>
<tr>
<td></td>
<td>≥ 10⁵</td>
<td>Flyer plate</td>
</tr>
<tr>
<td>Shear</td>
<td>≤ 0.1</td>
<td>Conventional shear test</td>
</tr>
<tr>
<td></td>
<td>0.1 to 100</td>
<td>Special servohydraulic frames</td>
</tr>
<tr>
<td></td>
<td>10 to 10⁰</td>
<td>Torsional impact</td>
</tr>
<tr>
<td></td>
<td>100 to 10⁴</td>
<td>Hopkinson (Kolsky) bar</td>
</tr>
<tr>
<td></td>
<td>10³ to 10⁴</td>
<td>Double-notch shear and punch</td>
</tr>
<tr>
<td></td>
<td>10⁴ to 10⁷</td>
<td>Pressure-shear plate impact</td>
</tr>
</tbody>
</table>

Table 2.3

Values of Strain Rate Sensitivity Exponent, m, and Constant C of Yield Strength of the Tested Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>m</th>
<th>ln C</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRAK-AR</td>
<td>0.045</td>
<td>10.72223</td>
</tr>
<tr>
<td>HRAK-Ann+TR</td>
<td>0.056</td>
<td>10.58935</td>
</tr>
<tr>
<td>HSLA-40</td>
<td>0.045</td>
<td>10.74515</td>
</tr>
<tr>
<td>HSLA-45-1</td>
<td>0.035</td>
<td>10.94544</td>
</tr>
<tr>
<td>HSLA-45-2</td>
<td>0.024</td>
<td>10.83534</td>
</tr>
<tr>
<td>HSLA-50</td>
<td>0.026</td>
<td>10.98135</td>
</tr>
<tr>
<td>HSLA-80-1</td>
<td>0.020</td>
<td>11.36871</td>
</tr>
<tr>
<td>HSLA-80-2</td>
<td>0.018</td>
<td>11.40914</td>
</tr>
</tbody>
</table>
Table 2.4

Standard Strain Rate Sensitivity
and New Strain Rate Parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>m</th>
<th>b</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF</td>
<td>0.011</td>
<td>0.039</td>
<td>0.150</td>
</tr>
<tr>
<td>HR</td>
<td>0.008</td>
<td>0.029</td>
<td>0.134</td>
</tr>
<tr>
<td>HSLA</td>
<td>0.004</td>
<td>0.010</td>
<td>0.102</td>
</tr>
<tr>
<td>DP</td>
<td>0.003</td>
<td>0.013</td>
<td>0.149</td>
</tr>
</tbody>
</table>

Table 2.5

Strain Rate Sensitivity for Different Microstructures
Determined by Strain Rate Jump Tests at 6.7 x 10^{-5} sec^{-1},
6.7 x 10^{-4} sec^{-1}, and 6.7 x 10^{-3} sec^{-1} (Ref. 46)

<table>
<thead>
<tr>
<th>Microstructures</th>
<th>( m ) low to intermediate strain rate</th>
<th>( m ) intermediate to high strain rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold-rolled</td>
<td>0.002</td>
<td>0.004</td>
</tr>
<tr>
<td>Normalized</td>
<td>0.002</td>
<td>0.004</td>
</tr>
<tr>
<td>Martensitic</td>
<td>0.003</td>
<td>0.005</td>
</tr>
<tr>
<td>Tempered martensitic</td>
<td>0.003</td>
<td>0.006</td>
</tr>
<tr>
<td>Ferrite-carbide</td>
<td>0.003</td>
<td>0.005</td>
</tr>
</tbody>
</table>
### Table 3.1
Chemical Compositions of the Sheet Steels Used

<table>
<thead>
<tr>
<th>AISI Designation</th>
<th>Thick. in.</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>V</th>
<th>Cu</th>
<th>Al</th>
<th>Cb</th>
<th>Zr</th>
</tr>
</thead>
<tbody>
<tr>
<td>035XF</td>
<td>0.085</td>
<td>0.070</td>
<td>0.40</td>
<td>0.007</td>
<td>0.017</td>
<td>--</td>
<td>0.08</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>050XF</td>
<td>0.077</td>
<td>0.081</td>
<td>0.96</td>
<td>0.017</td>
<td>0.003</td>
<td>0.27</td>
<td>--</td>
<td>0.04</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>100XF</td>
<td>0.062</td>
<td>0.070</td>
<td>0.43</td>
<td>0.006</td>
<td>0.023</td>
<td>--</td>
<td>--</td>
<td>0.11</td>
<td>0.056</td>
<td>0.064</td>
<td>0.08</td>
</tr>
</tbody>
</table>

### Table 3.2
Classification of the MTS Extensometer

<table>
<thead>
<tr>
<th>Range</th>
<th>Maximum Strain In./In.</th>
<th>Maximum Error In./In.</th>
<th>ASTM Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>0.50</td>
<td>0.00065</td>
<td>Between Classes B-2 and C</td>
</tr>
<tr>
<td>50%</td>
<td>0.25</td>
<td>0.00030</td>
<td>Between Classes B-2 and C</td>
</tr>
<tr>
<td>20%</td>
<td>0.10</td>
<td>0.00011</td>
<td>Between Classes B-1 and B-2</td>
</tr>
<tr>
<td>10%</td>
<td>0.05</td>
<td>0.00002</td>
<td>Between Classes A and B-1</td>
</tr>
</tbody>
</table>
Table 3.3

MTS Transducer Ranges and the Corresponding Load, Strain, or Displacement Values

<table>
<thead>
<tr>
<th>Transducer</th>
<th>Range</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load</td>
<td>100 %</td>
<td>160.0 Kips</td>
</tr>
<tr>
<td></td>
<td>50 %</td>
<td>50.0 Kips</td>
</tr>
<tr>
<td></td>
<td>20 %</td>
<td>20.0 Kips</td>
</tr>
<tr>
<td></td>
<td>10 %</td>
<td>10.0 Kips</td>
</tr>
<tr>
<td>Strain</td>
<td>100 %</td>
<td>0.50 In./In.</td>
</tr>
<tr>
<td></td>
<td>50 %</td>
<td>0.25 In./In.</td>
</tr>
<tr>
<td></td>
<td>20 %</td>
<td>0.10 In./In.</td>
</tr>
<tr>
<td></td>
<td>10 %</td>
<td>0.05 In./In.</td>
</tr>
<tr>
<td>Stroke</td>
<td>100 %</td>
<td>10.0 In.</td>
</tr>
<tr>
<td></td>
<td>50 %</td>
<td>5.00 In.</td>
</tr>
<tr>
<td></td>
<td>20 %</td>
<td>2.00 In.</td>
</tr>
<tr>
<td></td>
<td>10 %</td>
<td>1.00 In.</td>
</tr>
</tbody>
</table>

Table 3.4

Ramp Time 1 and the Corresponding Strain Rate

<table>
<thead>
<tr>
<th>Ramp Time 1 sec.</th>
<th>Strain Rate in./in./sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5000</td>
<td>0.0001</td>
</tr>
<tr>
<td>500</td>
<td>0.001</td>
</tr>
<tr>
<td>50</td>
<td>0.01</td>
</tr>
<tr>
<td>5</td>
<td>0.1</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Table 3.5

Tested Mechanical Properties of 100XF Sheet Steel

Virgin Material

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Strain Rate (in./in./sec.)</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LT-1</td>
<td>0.0001</td>
<td>122.44</td>
<td>122.44</td>
<td>9.4</td>
</tr>
<tr>
<td>LT-2</td>
<td>0.0001</td>
<td>126.07</td>
<td>126.07</td>
<td>9.7</td>
</tr>
<tr>
<td>LT-3</td>
<td>0.01</td>
<td>123.98</td>
<td>123.98</td>
<td>10.3</td>
</tr>
<tr>
<td>LT-4</td>
<td>0.01</td>
<td>125.91</td>
<td>125.91</td>
<td>10.3</td>
</tr>
<tr>
<td>LT-5</td>
<td>0.01</td>
<td>127.52</td>
<td>127.52</td>
<td>9.8</td>
</tr>
<tr>
<td>LT-6</td>
<td>1.0</td>
<td>129.06</td>
<td>129.06</td>
<td>---</td>
</tr>
<tr>
<td>LT-7</td>
<td>1.0</td>
<td>128.75</td>
<td>128.75</td>
<td>---</td>
</tr>
<tr>
<td>TT-1</td>
<td>0.0001</td>
<td>138.20</td>
<td>138.20</td>
<td>4.9</td>
</tr>
<tr>
<td>TT-2</td>
<td>0.0001</td>
<td>137.34</td>
<td>137.34</td>
<td>4.9</td>
</tr>
<tr>
<td>TT-3</td>
<td>0.01</td>
<td>140.11</td>
<td>140.11</td>
<td>6.1</td>
</tr>
<tr>
<td>TT-4</td>
<td>0.01</td>
<td>139.05</td>
<td>139.05</td>
<td>4.4</td>
</tr>
<tr>
<td>TT-5</td>
<td>1.0</td>
<td>144.11</td>
<td>144.11</td>
<td>8.0</td>
</tr>
<tr>
<td>TT-6</td>
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### Table 3.6

**Tested Mechanical Properties of 50XF Sheet Steel**

**Virgin Material**

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<tr>
<th>Test No.</th>
<th>Strain Rate (in./in./sec.)</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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<tbody>
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Table 3.7
Tested Mechanical Properties of 50XF Sheet Steel
2% Cold Stretched, Non-Aged Material

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<th>Strain Rate in./in./sec.</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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Table 3.8
Tested Mechanical Properties of 50XF Sheet Steel
8% Cold Stretched, Non-Aged Material

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<th>Strain Rate in./in./sec.</th>
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<th>$F_u$ (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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Table 3.9
Tested Mechanical Properties of 50XF Sheet Steel
2% Cold Stretched, Aged Material

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<th>Strain Rate (in./in./sec.)</th>
<th>( F_y ) (ksi)</th>
<th>( F_u ) (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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Table 3.10
Tested Mechanical Properties of 50XF Sheet Steel
8% Cold Stretched, Aged Material

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<th>( F_y ) (ksi)</th>
<th>( F_u ) (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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Table 3.11

Tested Mechanical Properties of 35XF Sheet Steel

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<th>$F_u$ (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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### Table 3.12
Tested Mechanical Properties of 35XF Sheet Steel
2% Cold Stretched, Non-Aged Material

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<th>$F_u$ (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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### Table 3.13
Tested Mechanical Properties of 35XF Sheet Steel
8% Cold Stretched, Non-Aged Material

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<th>Strain Rate</th>
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<th>$F_u$ (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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<td>29.9</td>
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Table 3.14
Tested Mechanical Properties of 35XF Sheet Steel
2% Cold Stretched, Aged Material

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<th>( F_y ) (ksi)</th>
<th>( F_u ) (ksi)</th>
<th>Elongation in 2-in. Gage Length (percent)</th>
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Table 3.15
Tested Mechanical Properties of 35XF Sheet Steel
8% Cold Stretched, Aged Material

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<th>( F_u ) (ksi)</th>
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<td>0.01</td>
<td>48.85</td>
<td>51.74</td>
<td>30.6</td>
</tr>
<tr>
<td>LT-4</td>
<td>0.01</td>
<td>49.70</td>
<td>52.34</td>
<td>30.7</td>
</tr>
<tr>
<td>LT-5</td>
<td>1.0</td>
<td>53.82</td>
<td>57.52</td>
<td>32.0</td>
</tr>
<tr>
<td>LT-6</td>
<td>1.0</td>
<td>53.53</td>
<td>57.55</td>
<td>31.1</td>
</tr>
<tr>
<td>TT-1</td>
<td>0.0001</td>
<td>45.25</td>
<td>47.60</td>
<td>25.3</td>
</tr>
<tr>
<td>TT-2</td>
<td>0.0001</td>
<td>45.64</td>
<td>47.65</td>
<td>28.7</td>
</tr>
<tr>
<td>TT-3</td>
<td>1.0</td>
<td>50.83</td>
<td>55.48</td>
<td>28.5</td>
</tr>
<tr>
<td>TT-4</td>
<td>1.0</td>
<td>51.25</td>
<td>56.01</td>
<td>28.1</td>
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</table>
Table 3.16
Average Tested Mechanical Properties of 100XF Sheet Steel
Longitudinal Tension, Virgin Material

<table>
<thead>
<tr>
<th>Strain Rate in./in./sec.</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Elongation (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>124.25</td>
<td>124.25</td>
<td>9.5</td>
</tr>
<tr>
<td>0.01</td>
<td>125.80</td>
<td>125.80</td>
<td>10.2</td>
</tr>
<tr>
<td>1.0</td>
<td>128.91</td>
<td>128.91</td>
<td>---</td>
</tr>
</tbody>
</table>

Table 3.17
Average Tested Mechanical Properties of 100XF Sheet Steel
Transverse Tension, Virgin Material

<table>
<thead>
<tr>
<th>Strain Rate in./in./sec.</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Elongation (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>137.77</td>
<td>137.77</td>
<td>4.9</td>
</tr>
<tr>
<td>0.01</td>
<td>139.58</td>
<td>139.58</td>
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</tr>
<tr>
<td>1.0</td>
<td>143.57</td>
<td>143.57</td>
<td>6.6</td>
</tr>
</tbody>
</table>
Table 3.18

Average Tested Mechanical Properties of 50XF Sheet Steel

Longitudinal Tension

<table>
<thead>
<tr>
<th>Amount of Cold Stretching</th>
<th>Strain Rate in./in./sec.</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Elongation (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin</td>
<td>0.0001</td>
<td>49.50</td>
<td>72.97</td>
<td>31.0</td>
</tr>
<tr>
<td>Virgin</td>
<td>0.01</td>
<td>51.60</td>
<td>74.87</td>
<td>27.0</td>
</tr>
<tr>
<td>Virgin</td>
<td>1.0</td>
<td>54.66</td>
<td>78.73</td>
<td>25.8</td>
</tr>
<tr>
<td>2%, Non-Aged</td>
<td>0.0001</td>
<td>56.40</td>
<td>73.01</td>
<td>27.0</td>
</tr>
<tr>
<td>2%, Non-Aged</td>
<td>0.01</td>
<td>58.67</td>
<td>74.50</td>
<td>25.5</td>
</tr>
<tr>
<td>2%, Non-Aged</td>
<td>1.0</td>
<td>62.67</td>
<td>80.32</td>
<td>27.0</td>
</tr>
<tr>
<td>8%, Non-Aged</td>
<td>0.0001</td>
<td>71.54</td>
<td>73.86</td>
<td>24.2</td>
</tr>
<tr>
<td>8%, Non-Aged</td>
<td>0.01</td>
<td>74.47</td>
<td>76.51</td>
<td>20.9</td>
</tr>
<tr>
<td>8%, Non-Aged</td>
<td>1.0</td>
<td>77.59</td>
<td>81.16</td>
<td>20.7</td>
</tr>
<tr>
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<td>0.0001</td>
<td>59.23</td>
<td>75.07</td>
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</tr>
<tr>
<td>2%, Aged</td>
<td>0.01</td>
<td>60.52</td>
<td>76.16</td>
<td>26.5</td>
</tr>
<tr>
<td>2%, Aged</td>
<td>1.0</td>
<td>63.21</td>
<td>81.27</td>
<td>28.8</td>
</tr>
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<td>0.0001</td>
<td>73.13</td>
<td>73.81</td>
<td>20.0</td>
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<tr>
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<td>0.01</td>
<td>73.15</td>
<td>75.20</td>
<td>21.5</td>
</tr>
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<td>75.77</td>
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</table>
Table 3.19

Average Tested Mechanical Properties of 50XF Sheet Steel

Transverse Tension

<table>
<thead>
<tr>
<th>Amount of Cold Stretching</th>
<th>Strain Rate (in./in./sec.)</th>
<th>$F_y$ (ksi)</th>
<th>$F_u$ (ksi)</th>
<th>Elongation (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin</td>
<td>0.0001</td>
<td>50.59</td>
<td>73.44</td>
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<td>0.01</td>
<td>53.21</td>
<td>74.74</td>
<td>26.5</td>
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<tr>
<td>Virgin</td>
<td>1.0</td>
<td>55.55</td>
<td>79.91</td>
<td>27.8</td>
</tr>
<tr>
<td>2%, Non-Aged</td>
<td>0.0001</td>
<td>59.29</td>
<td>74.90</td>
<td>23.1</td>
</tr>
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<td>2%, Non-Aged</td>
<td>1.0</td>
<td>68.48</td>
<td>81.29</td>
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<td>73.65</td>
<td>75.88</td>
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<td>82.00</td>
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<td>75.05</td>
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<td>64.79</td>
<td>83.09</td>
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<td>0.0001</td>
<td>74.30</td>
<td>74.95</td>
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<td>81.65</td>
<td>17.7</td>
</tr>
<tr>
<td>Amount of Cold Stretching</td>
<td>Strain Rate in./in./sec.</td>
<td>$F_y$ (ksi)</td>
<td>$F_u$ (ksi)</td>
<td>Elongation (percent)</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------</td>
<td>-----------</td>
<td>-----------</td>
<td>-------------------</td>
</tr>
<tr>
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<td>32.87</td>
<td>49.35</td>
<td>38.9</td>
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<td>36.40</td>
<td>51.76</td>
<td>36.8</td>
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<td>42.37</td>
<td>56.63</td>
<td>40.9</td>
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<td>49.47</td>
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<td>52.27</td>
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<td>57.05</td>
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<tr>
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<td>46.31</td>
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</tr>
<tr>
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<td>49.15</td>
<td>52.33</td>
<td>29.8</td>
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<tr>
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<td>52.90</td>
<td>57.21</td>
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<td>51.47</td>
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<td>56.85</td>
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<tr>
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<td>46.15</td>
<td>48.65</td>
<td>32.7</td>
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<td>49.27</td>
<td>52.04</td>
<td>30.7</td>
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<td>53.67</td>
<td>57.53</td>
<td>31.5</td>
</tr>
<tr>
<td>Amount of Cold Stretching</td>
<td>Strain Rate in./in./sec.</td>
<td>$F_y$ (ksi)</td>
<td>$F_u$ (ksi)</td>
<td>Elongation (percent)</td>
</tr>
<tr>
<td>---------------------------</td>
<td>-------------------------</td>
<td>------------</td>
<td>------------</td>
<td>---------------------</td>
</tr>
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</tr>
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<td>0.01</td>
<td>36.39</td>
<td>51.04</td>
<td>37.1</td>
</tr>
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<td>35.5</td>
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<td>55.93</td>
<td>34.8</td>
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<td>47.79</td>
<td>25.6</td>
</tr>
<tr>
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<td>52.47</td>
<td>56.37</td>
<td>27.7</td>
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<tr>
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<td>55.56</td>
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<td>45.45</td>
<td>47.63</td>
<td>27.0</td>
</tr>
<tr>
<td>8%, Aged</td>
<td>1.0</td>
<td>51.04</td>
<td>55.75</td>
<td>28.3</td>
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</table>
### Table 3.22

Ratios of Dynamic to Static Mechanical Properties for Three Sheet Steels Based on Tables 3.16 to 3.21

<table>
<thead>
<tr>
<th>Type of Sheet Steel</th>
<th>$(F_{yd})/(F_{ys})$</th>
<th>$(F_{ud})/(F_{us})$</th>
<th>$(\text{Elong.})<em>{yd}/(\text{Elong.})</em>{ys}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100XF-LT-Virgin</td>
<td>1.04</td>
<td>1.04</td>
<td>---</td>
</tr>
<tr>
<td>100XF-TT-Virgin</td>
<td>1.04</td>
<td>1.04</td>
<td>1.3</td>
</tr>
<tr>
<td>50XF-LT-Virgin</td>
<td>1.10</td>
<td>1.08</td>
<td>0.8</td>
</tr>
<tr>
<td>50XF-LT-2%, Non-Aged</td>
<td>1.11</td>
<td>1.10</td>
<td>1.0</td>
</tr>
<tr>
<td>50XF-LT-2%, Aged</td>
<td>1.07</td>
<td>1.08</td>
<td>0.99</td>
</tr>
<tr>
<td>50XF-LT-8%, Aged</td>
<td>1.04</td>
<td>1.07</td>
<td>---</td>
</tr>
<tr>
<td>50XF-TT-Virgin</td>
<td>1.10</td>
<td>1.09</td>
<td>1.04</td>
</tr>
<tr>
<td>50XF-TT-2%, Non-Aged</td>
<td>1.15</td>
<td>1.09</td>
<td>1.06</td>
</tr>
<tr>
<td>50XF-TT-2%, Aged</td>
<td>1.06</td>
<td>1.08</td>
<td>0.85</td>
</tr>
<tr>
<td>50XF-TT-8%, Aged</td>
<td>1.07</td>
<td>1.11</td>
<td>0.80</td>
</tr>
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<td>1.05</td>
<td>1.09</td>
<td>0.92</td>
</tr>
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<td>35XF-LT-Virgin</td>
<td>1.29</td>
<td>1.15</td>
<td>1.05</td>
</tr>
<tr>
<td>35XF-LT-2%, Non-Aged</td>
<td>1.20</td>
<td>1.15</td>
<td>1.04</td>
</tr>
<tr>
<td>35XF-LT-8%, Non-Aged</td>
<td>1.14</td>
<td>1.16</td>
<td>1.18</td>
</tr>
<tr>
<td>35XF-LT-2%, Aged</td>
<td>1.19</td>
<td>1.14</td>
<td>1.14</td>
</tr>
<tr>
<td>35XF-LT-8%, Aged</td>
<td>1.16</td>
<td>1.18</td>
<td>0.96</td>
</tr>
<tr>
<td>35XF-TT-Virgin</td>
<td>1.29</td>
<td>1.13</td>
<td>0.98</td>
</tr>
<tr>
<td>35XF-TT-2%, Non-Aged</td>
<td>1.22</td>
<td>1.17</td>
<td>1.04</td>
</tr>
<tr>
<td>35XF-TT-8%, Non-Aged</td>
<td>1.15</td>
<td>1.18</td>
<td>1.08</td>
</tr>
<tr>
<td>35XF-TT-2%, Aged</td>
<td>1.15</td>
<td>1.14</td>
<td>1.09</td>
</tr>
<tr>
<td>35XF-TT-8%, Aged</td>
<td>1.12</td>
<td>1.17</td>
<td>1.05</td>
</tr>
</tbody>
</table>

**Notes:**

- \((F_{yd})\) = dynamic yield stress for the strain rate of 1.0 in./in./sec.
- \((F_{ys})\) = static yield stress for the strain rate of 0.0001 in./in./sec.
- \((F_{ud})\) = dynamic ultimate stress for the strain rate of 1.0 in./in./sec.
- \((F_{us})\) = static ultimate stress for the strain rate of 0.0001 in./in./sec.
### Table 3.23

Values of Strain Rate Sensitivity $m$ for Three Sheet Steels Based on the Changes of the Yield Stresses at Different Strain Rates

<table>
<thead>
<tr>
<th>Type of Sheet Steel</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>$m_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100XF-LT-Virgin</td>
<td>0.003</td>
<td>0.005</td>
<td>0.004</td>
</tr>
<tr>
<td>100XF-TT-Virgin</td>
<td>0.003</td>
<td>0.006</td>
<td>0.004</td>
</tr>
<tr>
<td>50XF-LT-Virgin</td>
<td>0.009</td>
<td>0.013</td>
<td>0.011</td>
</tr>
<tr>
<td>50XF-LT-2%, Non-Aged</td>
<td>0.009</td>
<td>0.014</td>
<td>0.011</td>
</tr>
<tr>
<td>50XF-LT-8%, Non-Aged</td>
<td>0.009</td>
<td>0.009</td>
<td>0.009</td>
</tr>
<tr>
<td>50XF-LT-2%, Aged</td>
<td>0.005</td>
<td>0.009</td>
<td>0.007</td>
</tr>
<tr>
<td>50XF-LT-8%, Aged</td>
<td>0.000</td>
<td>0.008</td>
<td>0.004</td>
</tr>
<tr>
<td>50XF-TT-Virgin</td>
<td>0.011</td>
<td>0.009</td>
<td>0.010</td>
</tr>
<tr>
<td>50XF-TT-2%, Non-Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.016</td>
</tr>
<tr>
<td>50XF-TT-8%, Non-Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.006</td>
</tr>
<tr>
<td>50XF-TT-2%, Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.008</td>
</tr>
<tr>
<td>50XF-TT-8%, Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.005</td>
</tr>
<tr>
<td>35XF-LT-Virgin</td>
<td>0.022</td>
<td>0.033</td>
<td>0.027</td>
</tr>
<tr>
<td>35XF-LT-2%, Non-Aged</td>
<td>0.015</td>
<td>0.023</td>
<td>0.019</td>
</tr>
<tr>
<td>35XF-LT-8%, Non-Aged</td>
<td>0.013</td>
<td>0.016</td>
<td>0.014</td>
</tr>
<tr>
<td>35XF-LT-2%, Aged</td>
<td>0.008</td>
<td>0.029</td>
<td>0.019</td>
</tr>
<tr>
<td>35XF-LT-8%, Aged</td>
<td>0.014</td>
<td>0.018</td>
<td>0.016</td>
</tr>
<tr>
<td>35XF-TT-Virgin</td>
<td>0.018</td>
<td>0.037</td>
<td>0.028</td>
</tr>
<tr>
<td>35XF-TT-2%, Non-Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.021</td>
</tr>
<tr>
<td>35XF-TT-8%, Non-Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.015</td>
</tr>
<tr>
<td>35XF-TT-2%, Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.016</td>
</tr>
<tr>
<td>35XF-TT-8%, Aged</td>
<td>-----</td>
<td>-----</td>
<td>0.013</td>
</tr>
</tbody>
</table>

**Notes:**

$m_1$ = strain rate sensitivity based on the changes of yield stress between strain rates of 0.0001 in./in./sec. and 0.01 in./in./sec.

$m_2$ = strain rate sensitivity based on the changes of yield stress between strain rates of 0.01 in./in./sec. and 1.0 in./in./sec.

$m_3$ = strain rate sensitivity based on the changes of yield stress between strain rates of 0.0001 in./in./sec. and 1.0 in./in./sec.
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- 50XFLT-3, 8%, Aged
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- 50XFLT-9, Virgin
- 50XFLT-5, 2%, Aged
- 50XFLT-6, 8%, Aged