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Recommendations for Dynamic Tensile Testing of Sheet Steels

By

High Strain Rate Experts Group

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1. Introduction

Dynamic tensile testing of sheet steels is becoming more important due to the need for more optimized vehicle crashworthiness analysis in the automotive industry. Positive strain rate sensitivity, i.e. the strength increases with strain rate, offers a potential for improved energy absorption during a crash event.

Different types of testing techniques have been used to generate data under dynamic conditions. Each serves for a specific range of strain rates and provides specific type of information. Servo-hydraulic system, tensile Split Hopkinson Bar (SHB) system, compression Split Hopkinson Bar system, Single Bar (SB) system and drop weight system are some of the systems commonly used. New systems also are been developed in recent years to meet the increasing demand for dynamic testing. However, no guidelines are available as to the testing method, specimen dimensions, measurement devices, and other important issues which are critical to the quality of testing results. As the result, data from different laboratories are often not comparable. Quality of the testing data is, in general, not satisfactory. Signal damping and curve smoothing are often necessary to make the testing data usable.

With the increasing needs for tensile stress-strain data at dynamic conditions for steels, the International Iron and Steel Institute Committee on Automotive Applications (IISI-AutoCo) decide to develop a Recommended Practice for Dynamic Tensile Testing for Sheet Steels. A team composed of testing experts from Arcelor, Ispat Inland Inc. (now Mittal Steel), Nippon Steel Corporation and ThyssenKrupp Stahl, was commissioned in March 2003 to draft the document. Testing facilities and experiences from major testing laboratories with sheet steel experiences were compiled, including Arcelor, Colorado School of Mine, Ispat Inland Inc., JFE, Nippon Steel Corporation, POSCO, Sumitomo Metals, Technical University of Aachen, ThyssenKrupp Stahl, University of Dayton Research Institute and University of California at San Diego. This recommended testing practice is developed based on the information collected and experiences from the major steel companies in IISI. After the draft of the document was developed, a Round Robin test program was launched in early 2004 and completed in early 2005. Based on the results from the Round Robin test program, the document was modified again and the specimen geometry was further refined. Due to the limited time available, some testing techniques may not be included in this document. However, it is the belief of the team that this document covers most testing techniques for sheet steels and provides a starting point for a standard testing procedure in the near future.

2. Scope

This Practice is intended to provide guidelines for testing sheet steels under dynamic conditions. The range of strain rate included in this Practice is between 10^{-3} to 10^{3}/s, which is considered most relevant to vehicle crash events based on the experimental and FEA work for crashworthiness. Since testing standards are available for tensile testing at quasi-static (10^{-3}/s) condition, relevant testing standards, such as ASTM, EN, JIS, and ISO should be followed when applicable. Some of the standards are given in the Reference [1]. This document is for non-quasi-static tensile tests, including machine type, input method, specimen, clamping method and measurement systems. No attempt is made to cover curve smoothing techniques and constitutive models.

This document intends use of nomenclature and definitions (e.g. engineering stress, strain, strain rate, true stress, strain, and strain rate, etc.) as conventionally defined in existing test standards. However, when there is contradiction, ASTM E6 will apply. Special definitions are also given in the document when necessary.

3. Some Features of High Strain Rate Tensile Testing

To characterize the mechanical behavior of a material by uniaxial tensile tests, it is indispensable to measure the loading force associated with the change of the length of the specimen. At the quasi-static strain rate, a load cell is considered to deform homogeneously and the loading force is measured by a strain gauge attached to it. As the strain rate increases, the time needed to attain the homogeneity of elastic deformation within the load cell approaches that of the testing time, which leads to the necessity of considering the wave propagation within the load cell. Thus, there is a significant difference between quasi-static and high strain rate ranges in the load (stress) measurement.

At strain rates higher than about 10^{1} /s, the signal of the loading force is greatly perturbed by multiple passages of waves reflected within the load cell in a usual configuration. Thus, a special technique is required for the load measurement. This may be accomplished in two opposite ways. One is to shorten the load cell in the loading direction, thus reducing the time needed to homogenize the elastic deformation within the cell. The other way is to lengthen the load cell, in order to finish the measurement before the return of the elastic wave reflected at the other end. The former type of the load cell is actually used for servo-hydraulic system and continuous efforts have been devoted in order to have high eigen frequency. The latter approach is a basis for bar type system such as split Hopkinson pressure bar method and one bar method.

The direct measurement of strain is challenging at high strain rates. Extensometers used at quasi-static conditions do not have the necessary response characteristics and are normally physically too fragile at high strain rates. Non-contact extensometers, such as optical extensometer or laser interferometer, are becoming more popular due to their high sampling rate, faster response and much less physically demanding.

In addition to measurement systems, the specimen geometry should be determined carefully. To ensure higher strain rates and homogeneous deformation of the specimen in the gauge section, the length of the deformed zone of the specimen should be sufficiently short and a small radius should be used at the shoulder of the specimen. The smaller the radius at the shoulder of the specimen, the lower is the plastic deformation on the radius part. On the other hand the probability of having a rupture in the shoulder region of the sample increases drastically , so that a compromise must be found. All these conditions require a special geometry of the specimen, which is rather different from the one used at quasi-static strain rates. With much smaller gauge length compared with that for quasi-static testing, it is critical to include the uncertainty of the measurement devices when assessing the validity of the test results and conclusions.

Adiabatic heating is another issue for dynamic testing. The heat transformed from plastic deformation can be significant, as high as 60°C at 1000/s. Therefore, the stress-strain behavior at high strain rates is the result of strain rate and adiabatic heating. However, it is still an open issue if and how the effect of these two factors should be separated.

As clearly indicated by these features, the high strain rate testing requires special arrangements compared with testing at quasi-static conditions. The information collected from testing laboratories revealed that different techniques for loading and measurements are applied for different machines. However, there are common principles among these different testing practices, which are important to ensure the quality of the testing results. These common principals are the focus of this document.

4. Machine Types

In principle, any testing machine which can apply a uniaxial tensile load to the sheet steel specimen to failure with a specified high strain rate can be used to conduct dynamic tensile test. The load can be a constant load for a period of time, or an instant load wave used for very high strain rate. The machine should also have the proper measurement systems to measure and record the important parameters, such as strain, displacement and load.

In general, for the strain rate region of interest to crashworthiness, three types of testing systems are required. For testing at quasi-static condition and strain rates below 0.1/s, conventional load frame, either mechanical or servo-hydraulic, should be used. For strain rates higher than 0.1/s, both servo-hydraulic and bar type machines should be used. The servo-hydraulic type system can normally cover the strain rate range of 0.1 to 500/s, while bar type system covers the strain rates from 100 to 1000/s and higher. In special cases, 1000/s is possible for servo-hydraulic system. The strain rate increments – 1, 10, 100, 250, 500, 1000 s^{-1} – are sufficient for describing the strain rate sensitivity of steels materials. Figure 1 is a schematic representation of the applicable range of strain rates for the three testing systems.

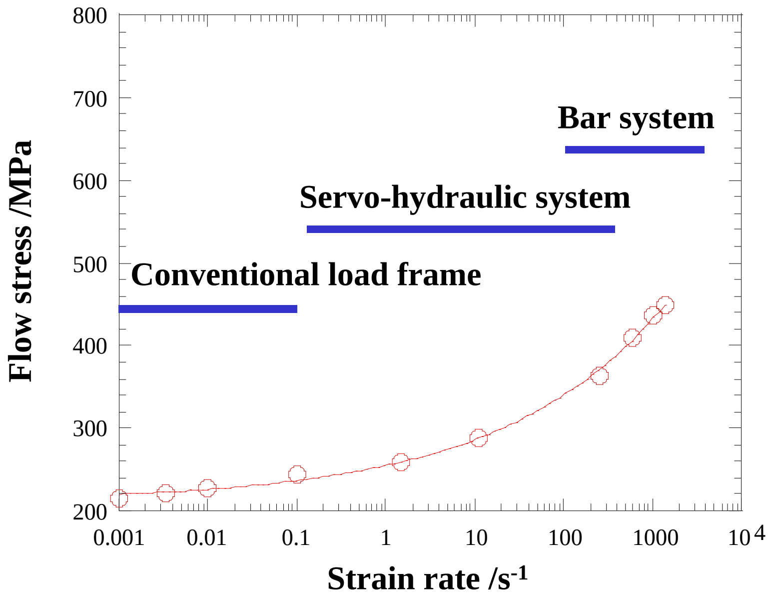


Figure 1 Typical ranges of strain rate covered by conventional load frames, servo-hydraulic machines and bar testing systems with curve shown for typical steel.

For the conventional load frame, all relevant existing standards apply. The high strain rate servo-hydraulic system is equipped with a much larger hydraulic power to achieve high actuator speed, as high as 30m/s. A picture of the system is shown in Figure 2. Loads are applied by the servo-hydraulic actuator as shown in the picture from the bottom. In some systems, the actuator is situated at the top.

The strain rate can be roughly calculated by the velocity of the actuator and the parallel length of the specimen, i.e.

$$\dot{\varepsilon} = \frac{V}{L}$$

where $\dot{\varepsilon}$ is the engineering strain rate, V is the velocity of the actuator and L is the initial parallel length of the specimen, which is the reduce section in the specimen with a constant width as defined in Figure 3. Thus, the maximum engineering strain rate achievable for a system can be calculated as,

$$\dot{\varepsilon}_{\max} = \frac{V_{\max}}{L_{\min}}$$

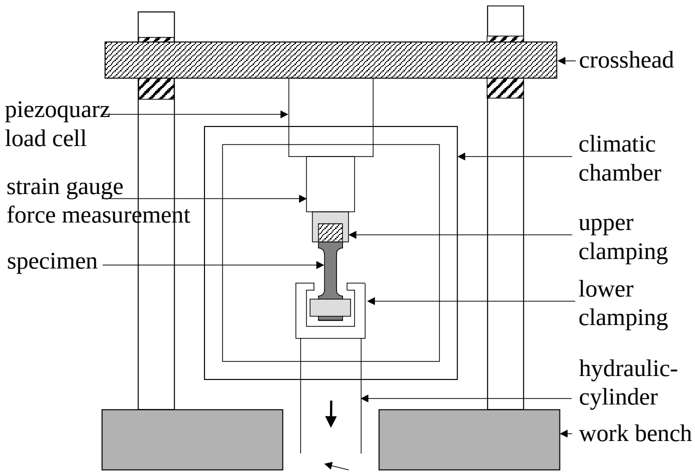


Figure 2 Schematic of Servo-hydraulic System (courtesy of Technical University of Aachen)

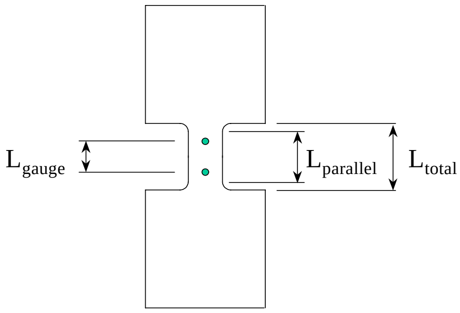


Figure 3 Definitions of dimensions in the gauge section. $L_{parallel}$ is the Parallel Length, which is the reduced section with a constant width. L_{gauge} is the Gauge Length when an extensometer is used, or lightly marked by indentations or ink. L_{total} is the Total Length that includes the parallel length and the shoulders.

V_{max} is the maximum speed of the actuator that is limited by the machine capability. L_{min} is the minimum initial parallel length of the specimen, which is controlled by the requirement to achieve the uniaxial stress condition throughout the parallel length of the specimen. The smaller the parallel length, the higher the maximum engineering strain rate is. When the radius of the shoulder is very small, as the case for many specimens designed for testing at high strain rates, the engineering strain rate can be roughly estimate by the total length L_{total}, the distance including the shoulders as shown in Figure 3, which is very easy to measure.

If the strain rate is measured by direct strain measurement on reduced gauge section, the values between yielding and necking shall be used. All testing reports should include how the strain rate is measured and calculated.

Servo-hydraulic systems can be of closed-loop or open loop. A closed-loop system ensures that the actuator moves at a constant speed. An open-loop system does not have the feedback signal, and therefore the actuator speed is not well controlled. The maximum strain rate achievable is limited by the strength of the steel tested, i.e. the peak load required, and the capacity of the machine. Higher strength steels often result in lower maximum strain rates. The maximum speed of the actuator for a closed-loop system is typically up to 1.0m/s, whereas for an open-loop system, higher maximum speed can be achieved.

A slack adaptor, a special device designed to provide a free traveling distance and thus to allow the actuator to achieve a specified velocity before loading the specimen, is often equipped in the servo-hydraulic high strain rate machine. This device is especially critical for testing at high strain rates in an open-loop system.

Bar system is normally used for strain rates higher than 500/s. Lower strain rates, such as 100/s, can be achieved with special configurations. The bar system was developed by Hopkinson [2] in 1914 and further advanced by Davies [3] and Kolsky [4]. Instead of applying a constant load throughout the test duration, an impact is applied to one end of the specimen, the stress wave created then propagates at the speed of sound through the specimen, resulting in very high strain rates. Split Hopkinson Bar (SHB) is a popular machine used so far. A schematic is shown in Figure 4. The specimen is mounted in between an incident bar and transmission bar. A striker tube is impacting the end of the incident bar so that a stress wave is created and propagated through the incident bar, specimen and the transmitter bar. Strain gauges are attached to the incident bar and transmitter bar as shown. Based on the propagation theory, the stress and strain in the specimen can be determined by the strains measured from these strain gauges. Details of the structure of a SHB and formulae used to calculate stresses and strains can be seen in an example in Appendix I. Single Bar system is another version of the bar system developed by Kawada et al. [5] as described in detail in Appendix II.

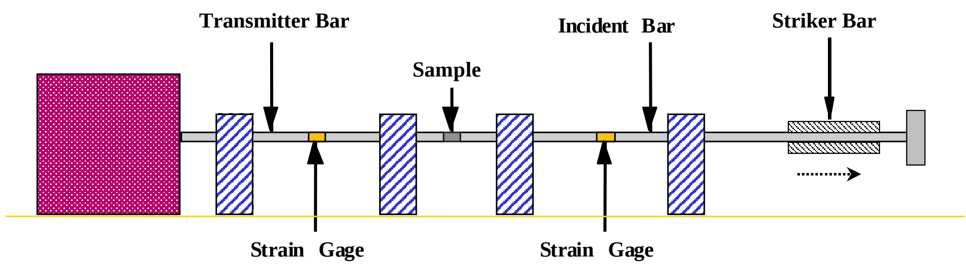


Figure 4 Schematic of tensile Split Hopkinson Bar System

The 'Sensing Block Method' system, a unique servo-hydraulic system currently under development potentially offers lighter machines and more economical high-volume testing capability. Evaluation of data quality and reliability is currently underway. Reference [7] describes this 'Sensing Block System' system.

5. Input Methods

In the servo-hydraulic system, load is applied to the specimen by an actuator which is driven by the hydraulic pressure as schematically shown in Figure 2. The load train should be perfectly aligned to avoid any bending on the specimen, and to ensure uniaxial stress condition. Alignment should follow ASTM 1012 or other relevant specifications. The loading train is carefully designed to apply a specified force with sufficiently high speeds.

For the tensile bar system, a stress wave is generated by launching a striker tube or hammer to strike the impact block or incident bar which is connected to a specimen as shown in Figure 4 for a typical Split Hopkinson Bar system. Similar to the servo-hydraulic system, perfect alignment is critical in reducing the noise level of the test signal.

For a SHB system, the duration of the stress pulse going through the specimen is limited by the length of the striker bar. Thus, the maximum strain that the specimen can achieve is limited by the configuration of the machine. When the total strain of the material is higher than the maximum strain achievable by the machine, the specimen will not break. A detail discussion of this limitation can be seen in Appendix III. However, this does not apply to the Single Bar system, since the load is applied to the specimen directly without the incident bar.

6. Specimens

Specimen geometry is determined by the following requirements:

1. Maximum strain rate required determines the parallel length. Specimens of small parallel lengths can achieve higher strain rates as mentioned in Section IV.

2. Parallel length of the specimen should be short enough at a given strain rate, in order to assure a homogeneous deformation of the specimen within the gauge section. In principle, the elastic wave should propagate thorough specimen before the plastic yielding of the material. For example, the parallel length is preferable to be less than 20 mm at a strain rate range of 10^3/s.

3. Radius at the shoulder of the specimen is recommended to be smaller than that of conventional tests, in order to reduce the constraint of the deformation around the shoulder on the gauge section. If the crosshead displacement is used to measure strains, the shoulder radius is recommended less than 5mm. A large shoulder radius can cause a significant amount of deformation to be included in the strain measurement resulting in measurement error.

4. Total length of the specimen depends on the clamping mechanism of each machine. For bar systems, the length of the specimen of the part which is not clamped by grips

should not be much longer than the length of the reduced section of the specimen, L_{total} , in order not to perturb propagations of the stress waves to the bars.

5. Uniaxial stress must be maintained along the gauge length, which is affected by parallel length, width and thickness. Numerical simulation is recommended for verification.

6. Grip section should have much larger cross section than gauge section to ensure negligible deformation and definitely no plastic deformation. This is critical when displacement measured by Linear Variable Differential Transducer (LVDT) is used for calculating strains. Plastic deformation in the grip sections can cause error in the strain measurement. A general rule for specimens with no holes in the grip section is that

   $$\frac{W_{gage}}{W_{grip}} < \frac{YS}{UTS}$$

   where W_{gauge} and W_{grip} are the width of the gauge section and grip section, respectively. YS and UTS are the yield strength and ultimate tensile strength of the steel being tested.

7. When steels of very thin gauge are tested, steel tabs of the same gauge can be added to the grip section to meet the no plastic deformation requirement.

8. A special grip section shall be designed in the specimen when load is measured by strain gauges attached to it.

Generally, the following rules of thumb should be applied:

$$\frac{L}{W} \geq 2$$

$$\frac{W}{t} \geq 2$$

$$\frac{W_{Gauge}}{W_{Grip}} \leq 0.5$$

where L is the parallel length. Smaller L value increases strain rate, but also increases error of strain measurement. Larger L will make the specimens prone to buckling. The radius at the shoulder should be taken into account when determining the L/W ratio. The smaller the radius, the larger the L/W ratio should be.

When W/t of less than 2 is used, the specimen often becomes too small (due to thin steel gauges). Caution must be taken to ensure valid of the results. In addition, selection of the specimen design should also consider steel strength, machine capacity, and other factors.

Surface of the specimens should be machine finish. The machined specimen surface should be free of cold work, cracks, notches and other surface defects which can cause stress concentration. Water-jet cutting and spark cutting are commonly used to limit the work hardening at the machined surface.

It is useful to test high strain rate specimens on quasi-static machines to compare the results (tensile strength and elongation) with those obtained on conventional specimens.

Specimen geometry of typical specimens used by testing laboratories is given in Appendix IV. It should be noted that the specimens included in the Appendix should not be considered the standard specimen dimensions recommended by this Practice. They are included for information only.

7. Clamping Methods

Proper clamping mechanism is critical to the data quality. The following should be considered:

1) Clamping mechanism should be stiff and of high natural frequency to reduce signal noise. It should also be light in mass to achieve the highest speed possible, but sufficient to ensure enough kinetic energy.

2) Clamping mechanism should ensure good alignment and no bending moment on the specimen.

3) For testing at higher strain rates using servo-hydraulic systems, a properly designed slack adaptor should be used to ensure the required strain rate during specimen deformation. A schematic of the slack adaptor is shown in Figure 5. In principle, the slack adaptor provides a free travel distance for the actuator to reach the specified speed. The weight of the slack adapter should be low in order to reduce the impact on the specimen.

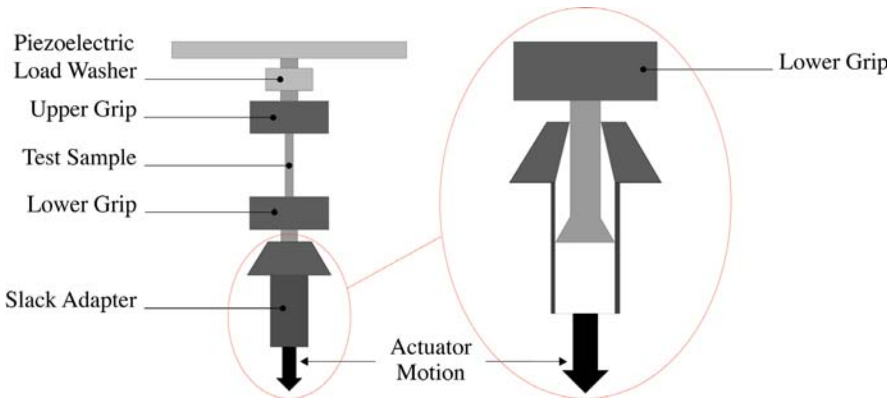


Figure 5 Schematic of Slack Adapter (Courtesy of Colorado School of Mines)

4) For testing at strain rates higher than 500/s using bar techniques, either Split Hopkinson Bar (SHB) or Single Bar method, clamping fixtures are mounted directly to the input bars. It is recommended that the clamping fixture uses the same material as the input bar and of the same diameter to ensure the least impedance change when the stress wave propagates through the loading train. If different material or size is used, proper adjustment should be made in the calculation of the stress and strain.

8. Measurement Devices

Strain measurement

Strain in tensile tests is represented by the ratio between the relative displacement of two points in the gauge section, i.e. gauge length, of a specimen and their initial distance, engineering strain. Generally, an extensometer attached to the gauge section of the specimen is used and the measurement is very accurate. At higher strain rates, it is almost impossible to use this method due to inertia effects of the extensometer. Thus, strain measurement at high strain rates usually uses the relative displacement of the points selected from the place other than the gauge section of the specimen, for example, the displacement between grips of the specimen or the displacement of the actuator measured by LVDT.

When the strain is not measured directly from the gauge section of the specimen, special attention should be paid to assure the dominant deformation in the gauge section of the specimen. The deformation in the remaining sections of the loading train falsely increases the strain measured and normally gives incorrect and much lower initial slope of the stress-strain curve in the elastic region.

The following devices can be used to measure strain. Because many of the measurement devices are still in the development stage, the quality of the measurement devices varies significantly by different manufacturers. Cautions must be taken to ensure quality of testing results.

1. Conventional low inertia extensometer can be used for strain rates up to 10/s.

2. Strain gauges for large strain measurement attached to the gauge section of the specimens can be used for strain measurement. The maximum strain is limited by the commercial strain gauges available, normally around 10% . At present, using strain gauge is the best method to record stress strain data at small strain regions when yield strength and yield point elongation is of interest. However, due to the increased time and equipment needed, it should only be applied in special cases or for base research investigations To compensate for the coil set, strain gauges may be attached on both surfaces of the specimen.

3. An Electro-optical, Doppler or laser extensometer of good quality is highly recommended for strain rates up to 10^3/s. The device is capable of recording strains throughout the test.

4. Displacement measured by LVDT can be used to calculate strain using the following formula:

$$\varepsilon = \frac{\Delta L}{L}$$

where ε is engineering strain, L is the initial parallel length of the specimen and ΔL is the displacement as measured by LVDT and corrected for machine stiffness. This formula can provide sufficiently good strain measurement only when the deformation in the parallel section is dominant, and that in the remaining sections of the loading train is negligible comparing with the deformation in the reference section.

In general, LVDT is not recommended as the sole device for strain measurement. It can be used to provide back up data for other measurement devices. When no other devices are available, using displacement measurement by LVDT in combination with attaching strain gauges in the gauge section to measure small strains can offer satisfactory strain measurement for the full strain region.

5. For bar type system, strain gauges attached to the bars are used for strain measurement. The displacement of bar / specimen interfaces can be obtained by the signals measured by the strain gauges based on an analysis of the propagation of the elastic waves in the bars. This method is capable of recording strains throughout the test.

6. A constant nominal strain rate throughout the test is essential to the quality of data. The strain rate must be calculated during the test to insure that a constant rate is achieved.

7. Fracture elongation of the specimens should also be determined manually after the test to verify the strain measurement.

Stress measurement

Stress signal from dynamic testing often exhibits significant oscillation due to ringing of the loading system at high strain rates. To reduce the stress oscillation, besides careful designs of testing machine, clamping system and specimen, proper selection of the load measurement device is critical. Load measurement devices should be close to the specimen as possible in order to reduce the phase difference between the strain measurement and stress measurement.

In general, stress can be measured in the following two ways:

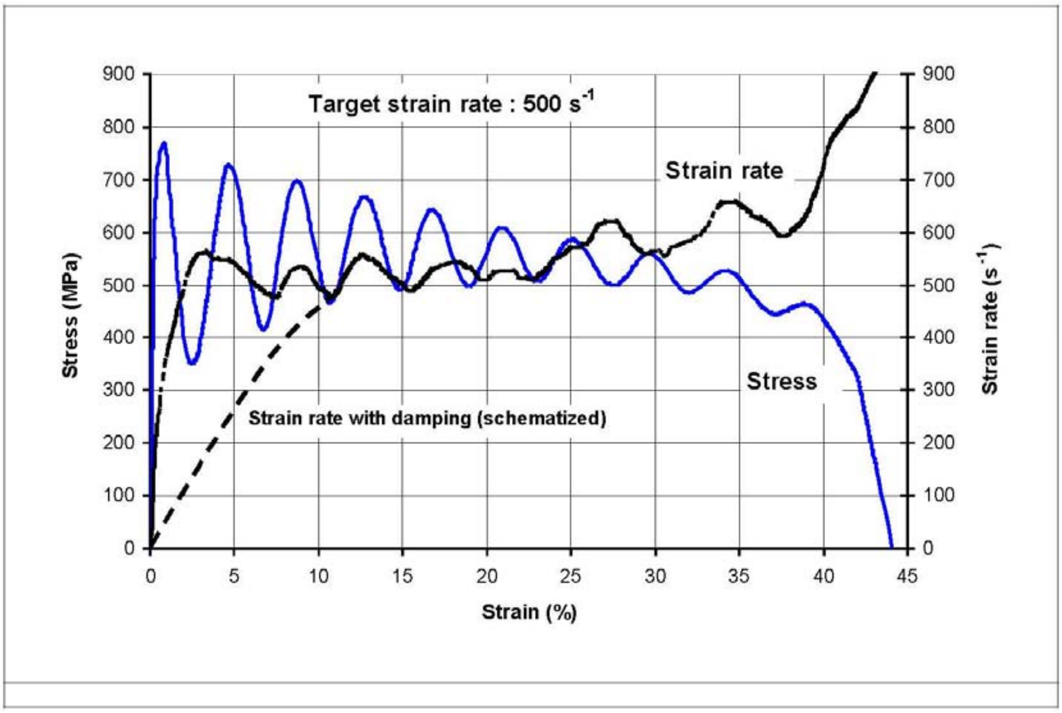
1. Measure the load, P, by using a commercial load cell and calculated the engineering stress by $\sigma = P/S$, where S is the initial area of the cross section.

2. Measure the engineering elastic strain, ε_e, by attaching strain gauges (elastic) on the location outside the gauge section of the specimen where the deformation is elastic. Load is calculated by using the Young's modulus, i.e. $P = \varepsilon_e * E * S$. The location of the strain gauges can be in the grip section of the specimen, or in a separate specially designed grip [6, 7].

Whichever system is used, careful calibration is important to ensure accurate stress measurement. Especially, when the method (2) is used, strain gauges attached on the specimen shall be calibrated for each specimen. Load measuring errors are introduced if every specimen is not calibrated. The following devices are recommended:

1. Conventional strain gauge instrumented load cell is used for strain rates up to 10/s.
2. Piezo-electric load washer is used for <100/s
3. Load measurement by strain gauges:
   - When strain gauges are attached to the grip section of the specimen, one strain gauge on each side of specimen is preferred to compensate the effect of coil set.
   - When strain gauges are attached to a separate grip, careful design of the grip is imperative to ensure sufficient load range, minimum noise, and good measurement repeatability and reliability.
   - In the servo-hydraulic system, the section where strain gauges attach should not be mounted to the actuator where acceleration applies.
   - For bar systems, stress is calculated by using the strain measured from the strain gauge attached to the transmitter/output bar. The location of the strain gauge should be such that the stress measurement is completed before the transmitted stress wave reflected back from the other end of the transmitter/output bar (see Appendices I and II).

In addition to stress oscillation originated at stress measurement devices, there is inevitable elastic response of the tested materials due to a sudden loading. The characteristic might be represented by a rise time of a load signal. In actual testing system, there exists a fairly long rise time, thus the oscillation of this origin does not cause any significant effects on the measured signals. For example, in the split Hopkinson bar method the incident wave is partially dispersed during its propagation in the incident bar and shows a relatively long rise time. Damping to reduce such oscillation should be used very carefully. Too much damping limits the strain rate at the beginning of the deformation and changes the apparent material behavior. If damping methods must be applied, the information of strain rate versus strain becomes indispensable. This is schematically shown in Figure 6. As seen in Figure 6, if the strain range of interest is greater than 10%, damping may be acceptable, but if the strain range of interest is less than 10% damping is not acceptable.



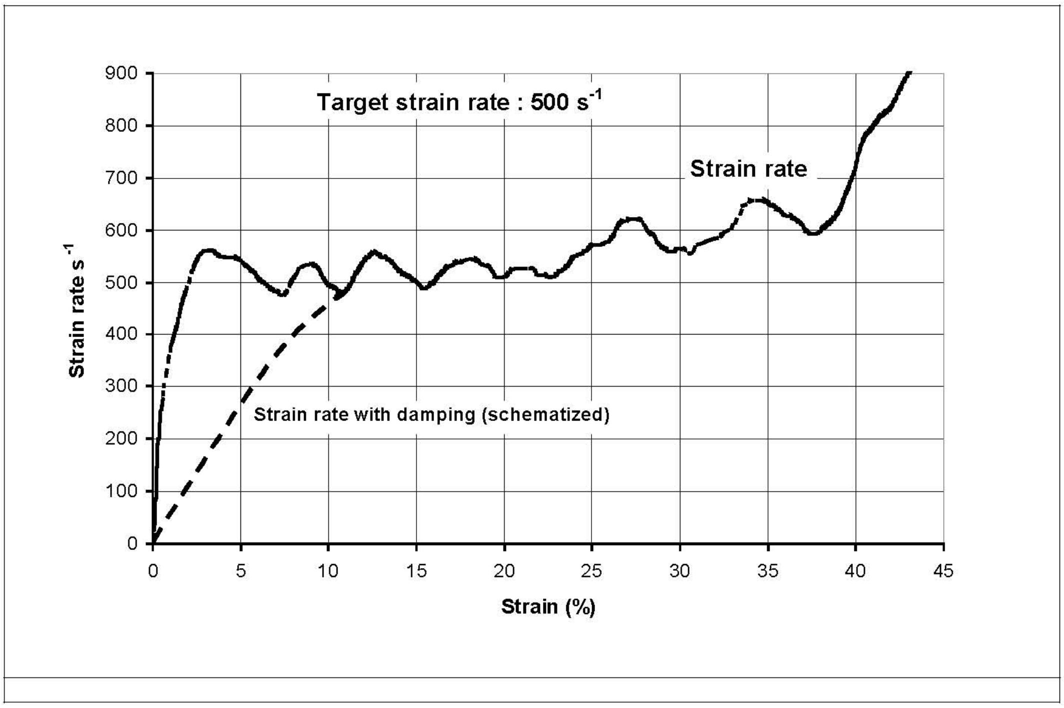


Figure 6. Effect of damping on strain rate (schematic)

9. Assessment and Improvement of Data Quality

Load oscillation in the stress strain curve is one of the major quality issues for dynamic testing. Figure 7 shows engineering stress strain curves measured at 100/s and 500/s on a servo-hydraulic system. Notice not only the oscillation of the load becomes severe at 500/s, the engineering stresses at strains below 15% also increase much more than in the higher strain region. The drastic increase of flow stress at the low strain region may be the effect of initial impact of the actuator. It is therefore very important to assure that the stress oscillation is limited and the change of the shape of the stress strain curve is fully understood. The experiences for several testing laboratories show that using strain gauges attached to the specimen grip section can significantly reduce load oscillation as shown in Figure 8 when a piezo-electric load washer is replaced by strain gauges at the grip section of the specimen.

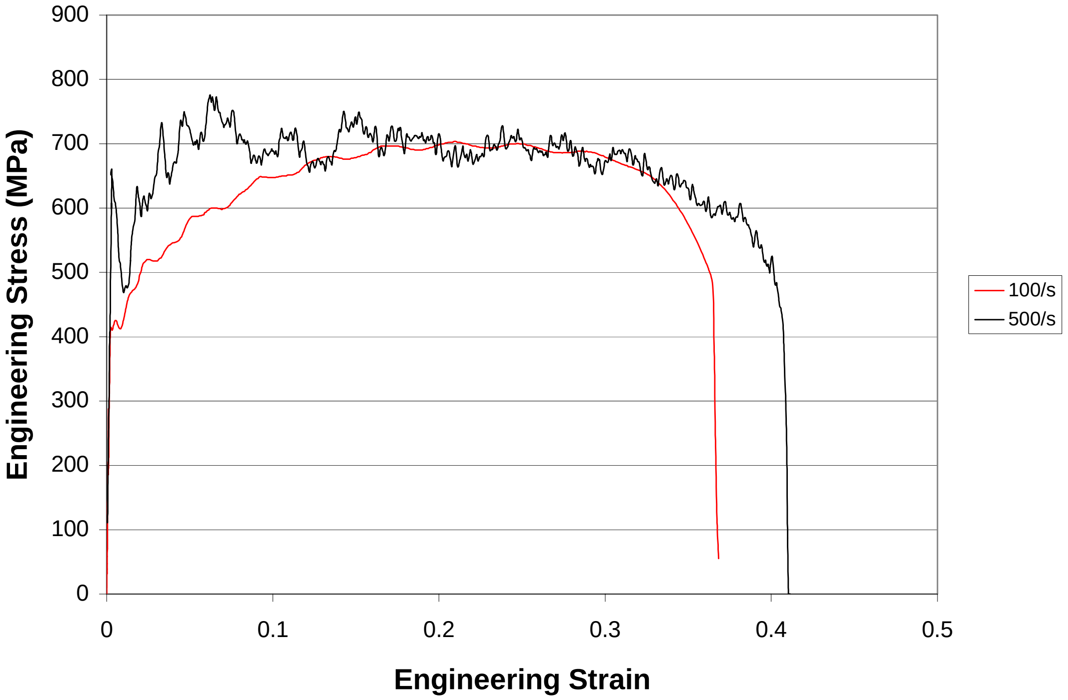


Figure 7 Engineering stress-strain curve at 100/s and 500/s. (Courtesy of Ispat Inland Inc.)

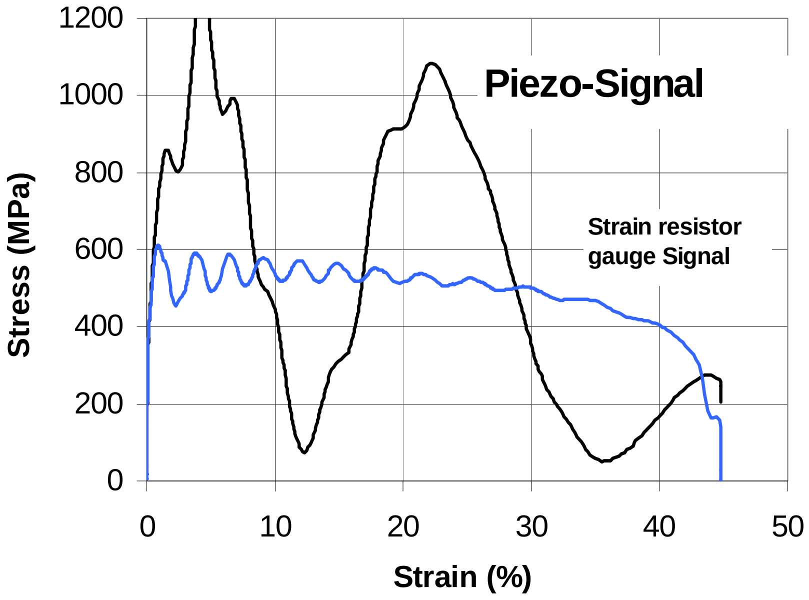


Figure 8 Improvement of engineering stress-strain curve using strain gauges at the grip section of the specimen (strain rate $500s^{-1}$)

Incorrect slope of the stress strain curve in the elastic region is another quality issue for dynamic testing results. The slope is often much lower than the Young's modulus. As discussed in Section 8, the origin of lower slope lies in the accuracy of the strain measurement. When a strain gauge is attached to the gauge section of the specimen, the strain measured normally offers the best linear section of the stress strain curve. Proper specimen design and measurement setting would offer fairly good results when other strain measurement techniques are used.

Continuous improvement of data quality requires holistic approach by investigating the testing system, clamping mechanism, specimen design and measurement devices. An example of eliminating the false upper yield point by carefully eliminating the microvibration of the output bar for a Single Bar system is shown in Appendix V.

Generating quality data often incurs significantly more testing work and higher cost. For example, adding strain gauges for both strain and stress measurements will not only add the equipment needed for data acquisition and the number of consumable strain gauges, but also significantly add test preparation time and thus reduced productivity. Depending on the purpose of testing and the amount of work load, balance between quality, cost and efficiency must be evaluated properly.

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   - ASTM E74 (American Society for Testing and Materials) Practice of Calibration of Force-Measuring Instruments for Verifying the Force Indication of Testing Machines
   - B 0801 (Korean Standards Association) Test Pieces for Tensile Test for Metallic Materials
   - B 5518 (Korean Standards Association) Extensometers Used in Metallic Material Tensile Testing
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7. S. Tanimura, K. Mimura, and T. Umeda, "New Testing Techniques to Obtain Tensile Stress-Strain Curves for a Wide Range of Strain Rates", presented at DYMAT, Porto, Portugal, Sept. 8-12, 2003

Appendix I

Tension Split Hopkinson Bar (University of Dayton Research Institute)

1. Machine Capacity and Major Specifications

DTSHB configuration has been routinely employed in our laboratory to characterize tensile behavior of various grades of automotive sheet steels at strain rates from 200-1500/s over the last 3 years. Incident and transmitting bars of the DTSHB are made of 2.44-m (8 feet) long 25.4-mm diameter 7075 aluminum (Fig. 1). Two (1000 Ω) strain gauges are mounted on each bar 48-inches away from the specimen to monitor strains in the pressure bars. A 0.76-m long aluminum striker tube is generally launched around the incident bar and the impact of the aluminum tube against the aluminum anvil (rigidly attached to the end of the incident bar) generates a tensile stress pulse in the incident bar (Fig. 1). We also have aluminum striker tubes of shorter lengths for shorter loading pulse. For materials with extremely low tensile strength Nylatron (Nylon/Graphite composite) striker tubes are recommended to produce low amplitude incident tensile pulses.

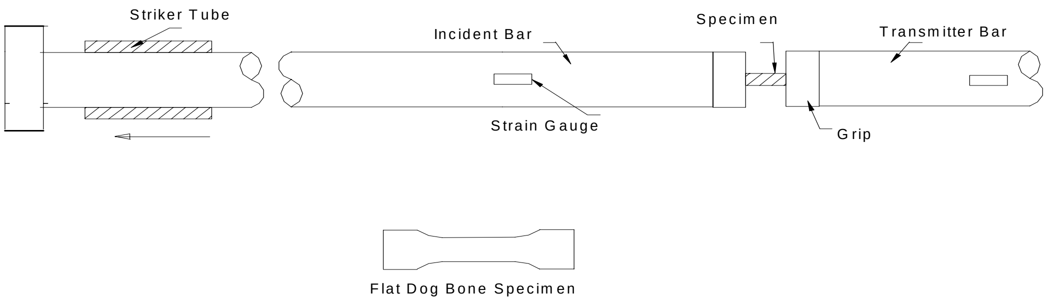


Figure 1. Schematic of the Direct Tension Split Hopkinson Bar

2. Specimen: Size (Dimensions) and Fabrication

Tension specimens of automotive sheet steels are generally dog-bone shaped (e.g., ASTM D 1822 Type L, Fig. 2) and are fabricated either in our machine shop or using water jet cutting technique (RPG Industries, Tipp City). These are placed in specially designed grips screwed into the threaded incident and transmitting aluminum bars. Tension specimens with threaded ends (Fig. 3), generally fabricated from 6.35-mm diameter bar stock or 6.35-mm thick sheet stock can also be tested. To accept the threaded specimen, aluminum anvils are attached to the incident and transmitting bar ends with threaded holes. We also have a capability of tensile characterization of different materials available in 6.35-mm diameter bar stock or 6.35-mm thick sheet stock (threaded specimens) using our 12.5-mm diameter Indirect Tensile Hopkinson (Inconel) Bar configuration. This SHB configuration allows the tensile testing to be conducted at high temperatures to 1200^{o}F.

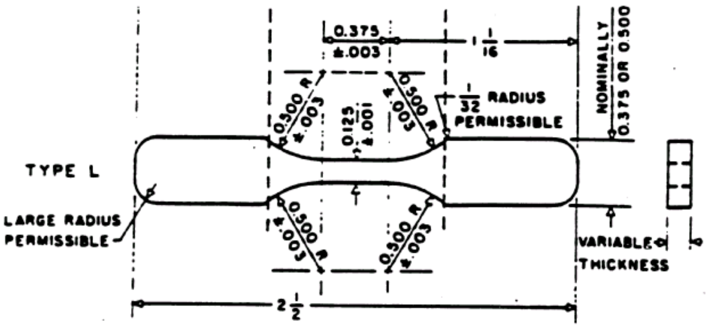


Figure 2. ASTM D1822 Type L Tension Specimen

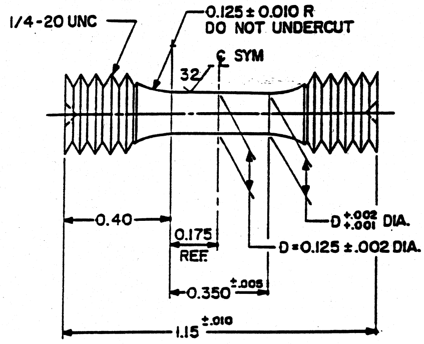


Figure 3. Threaded tensile specimen fabricated from 6.35-mm diameter bar or 6.35-mm thick sheet stock

3. Measurement Method

A tensile stress pulse is generated in the incident bar by the impact of the striker tube with the flange at the end of the incident bar. This tensile pulse propagates towards the incident bar/specimen interface and subjects the specimen to a tensile load. A portion of this incident tensile pulse, ε_i, is transmitted through the specimen ε_t and the remainder is reflected back in the incident bar ε_r. The amplitude of the incident, reflected, and transmitted pulses are recorded by the strain gauges mounted on the pressure bars. Incident, reflected, and transmitted stress pulse data are analyzed following the procedure given below.

Using the recorded strains, the stress (σ), strain (ε) and strain rate ($\dot{\varepsilon}$) in the specimen are determined using Equations (1-3)

$$\sigma(t) = E\frac{A_b}{A_s}\varepsilon_t(t) \tag{1}$$

$$\varepsilon(t) = -\frac{2 \cdot C_o}{L}\int_0^t \varepsilon_r(t)dt \tag{2}$$

$$\dot{\varepsilon}(t) = -\frac{2 \cdot C_o}{L}\varepsilon_r(t) \tag{3}$$

where A_b and A_s are the cross-sectional area of the pressure bar and the specimen in the gauge section, respectively, and L is the gauge length of the specimen. The stress, strain, and strain rate are the average values and are determined by assuming a uniform uniaxial stress-state condition, which implies that

$$-\varepsilon_r = \varepsilon_i - \varepsilon_t \tag{4}$$

The strain rate in an experiment (Equation 3) depends on the magnitude of the reflected pulse ε_r, which is a function of the magnitude of the incident pulse ε_i and that of the transmitted pulse ε_t. The magnitude of the transmitted pulse is bounded by the flow stress of the material, as given by Equation (1). Assuming that the compressive strength of the material is constant, the magnitude of ε_r depends on the magnitude of ε_i only. Thus, the specimen strain rate is directly related to ε_i, which is given by:

$$\varepsilon_i = \frac{1}{2 \cdot E} \cdot C_o \ \rho \cdot V_s \tag{5}$$

where V_s is the striker bar velocity. Consequently, one way of changing the specimen strain rate is to change the striker bar velocity. An alternative way to change the specimen strain rate is change the specimen gauge length. In fact, the flow stress of the material is not constant, but is a function of the strain rate and temperature. Therefore, a fine adjustment in the striker tube velocity is always needed to achieve the predetermined strain rate.

Appendix II

One Bar Method (Nippon Steel Corporation)

One-bar technique has been developed by Kawata et al. (On high-velocity brittleness and ductility of dual-phase steel and some hybrid fiber reinforced plastics, Recent advances in composites in the United States and Japan, ASTM STP 864, Am. Soc. for Testing and Materials, Philadelphia, 700., 1985), based on the Hopkinson bar method. As shown in Figure 1, the testing system consists of a hammer, an impact block, a specimen and an output bar. When the impact block is given an impact by the hammer, the specimen is deformed in tension. At the instant of the impact, a transmitted wave starts to propagate in the output bar, its amplitude being proportional to the stress in the specimen. This wave is recorded by a strain gauge attached to the output bar at section C, situated at a distance *a* from section B. In addition, an electro-optical extensometer is used to measure the velocity $V(t)$ of the impact block, which is integrated to give the displacement of section A

$$u_A = \int_0^t V(t) dt . \tag{1}$$

An analysis of the propagation of the elastic waves in a bar enables to derive the displacement u_B of section B, from the strain of the transmitted wave $\varepsilon_\mathrm{g}(t)$ at section C. The propagation of waves in a bar is considered as a one-dimensional problem, when the lateral inertia can be neglected. Considering the delay of the wave propagation, u_B can be expressed in terms of ε_g as

$$u_\mathrm{B} = c\int_0^t \varepsilon_\mathrm{B}(t)\, dt = c\int_0^t \varepsilon_\mathrm{g}(t + a/c)\, dt . \tag{2}$$

The elongation of the specimen is the difference between the displacements at sections A and B. By using Eqs. (1) and (2) the engineering strain and the engineering strain rate of the specimen may be expressed as

$$\mathrm{e}(t) = \frac{u_\mathrm{A} - u_\mathrm{B}}{L_0} = \frac{1}{L_0}\int_0^t \left[V(\tau) - c\varepsilon_\mathrm{g}\left(\tau + a/c\right)\right] d\tau, \tag{3}$$

$$\dot{\mathrm{e}}(t) = \frac{1}{L_0}\left[V(t) - c\,\varepsilon_\mathrm{g}(t + a/c)\right], \tag{4}$$

where L_0 is the length of the specimen. The axial force $F(t)$ at section B can also be determined from the amplitude of the transmitted wave $\varepsilon_\mathrm{g}(t)$ as

$$F(t) = E_\mathrm{bar}\, A_\mathrm{bar}\, \varepsilon_\mathrm{B}(t) = E_\mathrm{bar}\, A_\mathrm{bar}\, \varepsilon_\mathrm{g}(t + a/c). \tag{5}$$

Thus, the nominal stress in the specimen becomes

$$\sigma_n(t) = \frac{F(t)}{A_0} = \frac{A_{bar}E_{bar}}{A_0}\,\varepsilon_g(t + a/c). \tag{6}$$

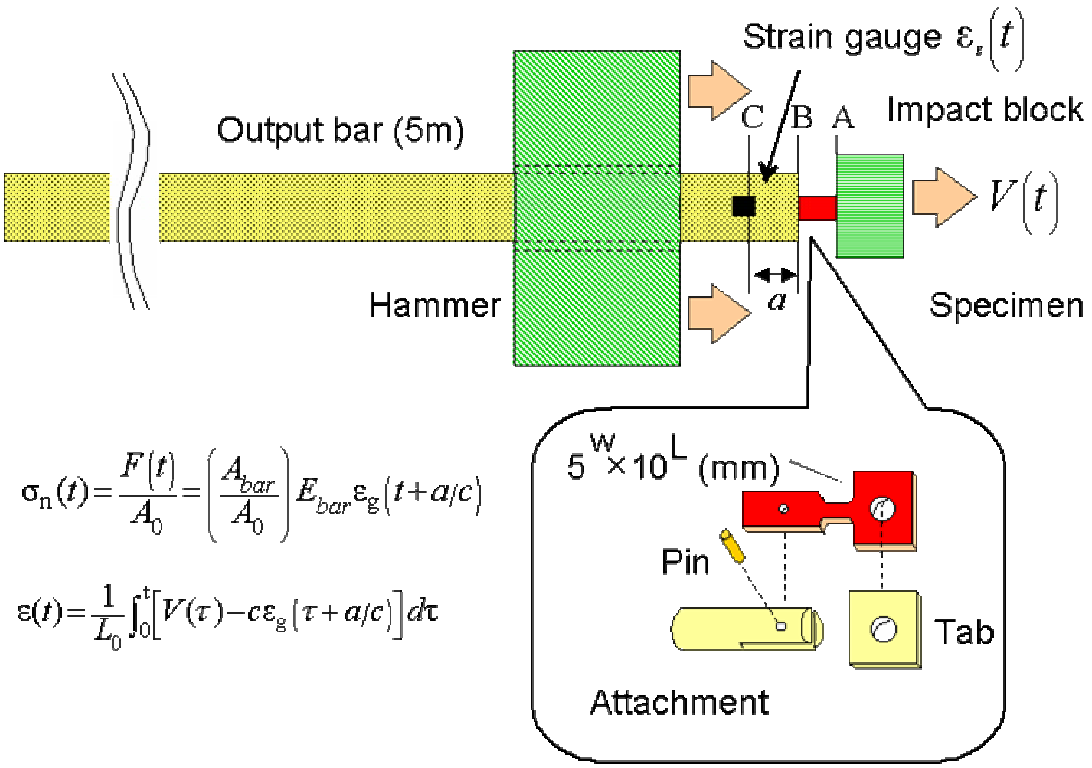


Figure 1 Schematics of one bar method high strain rate tensile test machine

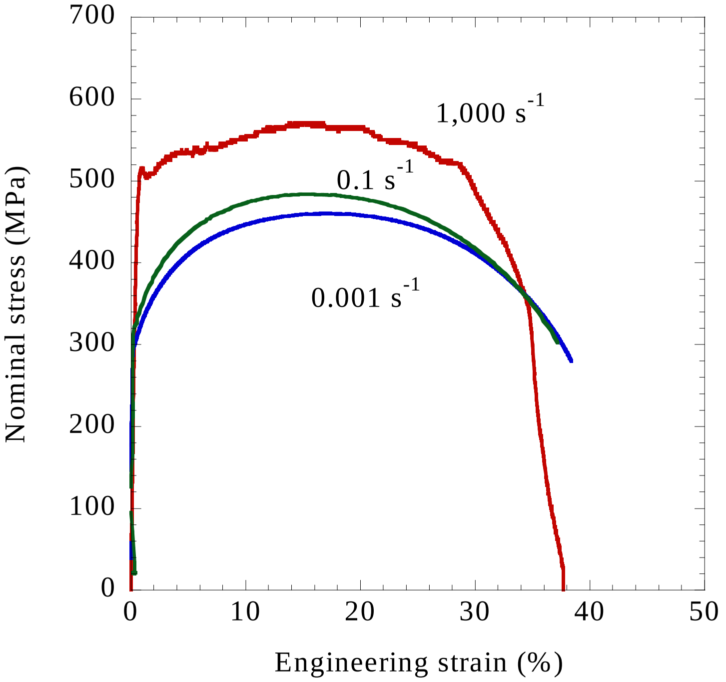


Figure 2 Example of stress-strain curves measured by one bar method ($1{,}000 s^{-1}$) and conventional method ($0.001, 0.1\ s^{-1}$)

Appendix III

Calculation of Strain Limit for SHB System

The duration of the stress pulse going through the specimen in a Split Hopkinson Bar system is dependent on the length of the striker bar and thus is fixed for a test machine. In general, the duration of the stress pulse can be expressed as follows for a system in Figure 3,

$$T = \frac{2l_s}{C_0}$$

where l_s is the length of the striker tube, $C_0 = \sqrt{\frac{E}{\rho}}$, and T is the transition time, or the duration of the stress pulse. E and ρ are the Young's modulus and density of the striker tube, respectively. For an Inconel striker bar of 0.76m long, for example, T can be calculated to be 315 μs.

The total strain of the steel specimen achieved during this time duration is proportional to the strain rate,

$$\varepsilon_{total} = T * \dot{\varepsilon}$$

When the strain rates is high, the total strain achievable can be higher than the total elongation of the steel. However, if the strain rate is low, the total strain achievable can be lower than the total elongation of the steel, meaning the duration of the stress wave is not long enough to break the specimen. The minimum strain rate for a SHB system is thus dependent on the strain required for the steel. Normally, uniform elongation is the minimum strain required for a meaningful tensile test at high strain rates. The minimum strain rate for a SHB system can be estimated as

$$\dot{\varepsilon}_{\min} = \frac{UE}{T}$$

where UE is the uniform elongation of the steel.

Appendix IV

Examples of Specimen Geometry

It should be noted that the specimens included in the Appendix should not be considered the standard specimen dimensions recommended by this Practice. They are included for information only.

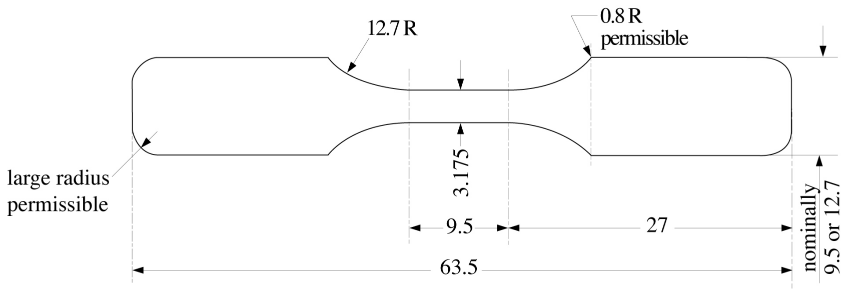


Figure 1 Specimen used by UDRI

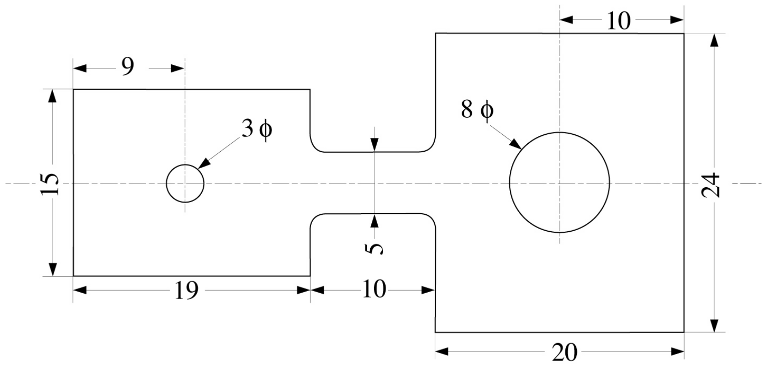


Figure 2 Specimen used by JFE

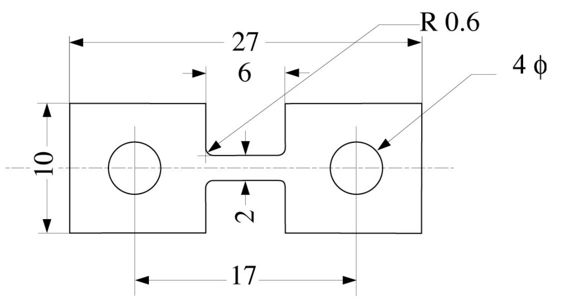


Figure 3 Specimen used by Sumitomo Metals

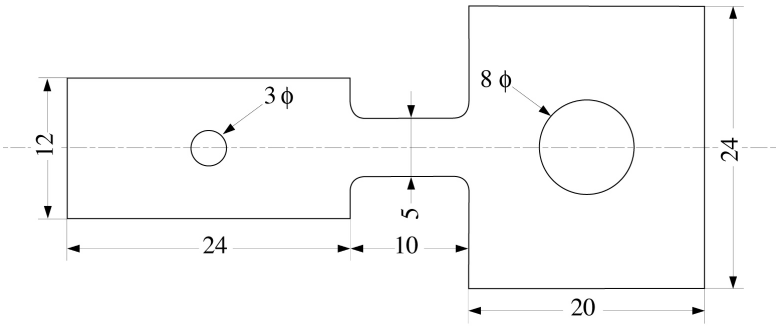


Figure 4   Specimen used by Nippon Steel Corporation

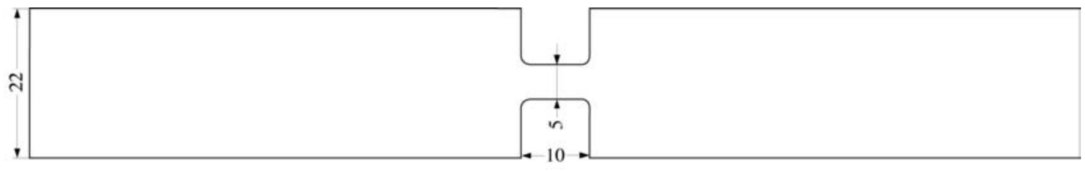


Figure 5 Specimen used by Nippon Steel Corporation

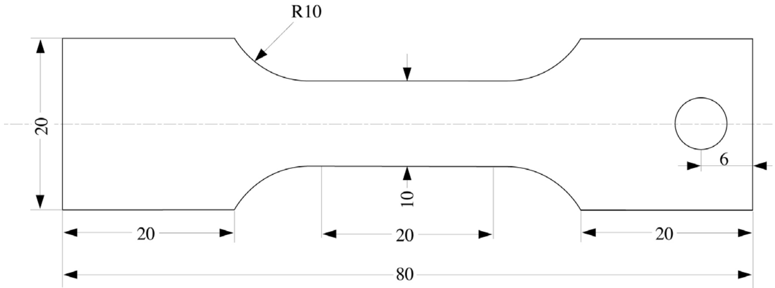


Figure 6 Specimen used by Technical University of Aachen

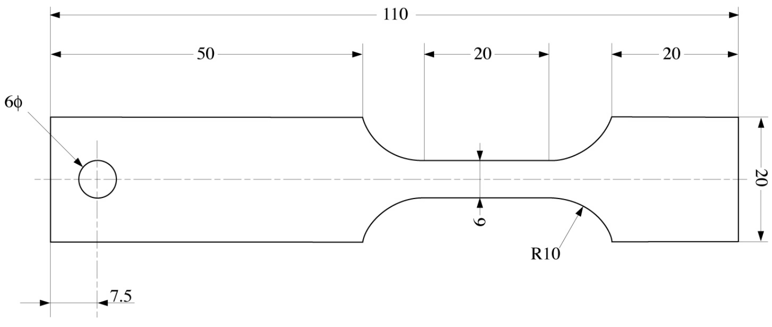


Figure 7 Specimen used by Technical University of Aachen

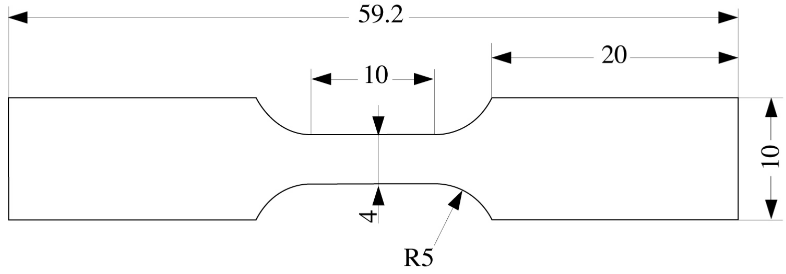


Figure 8 Specimen used by Arcelor

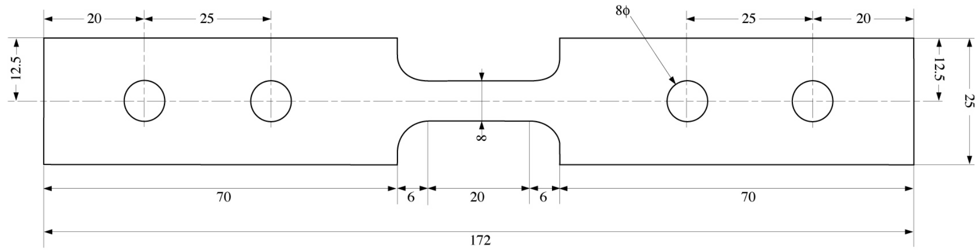


Figure 9 Specimen used by Arcelor

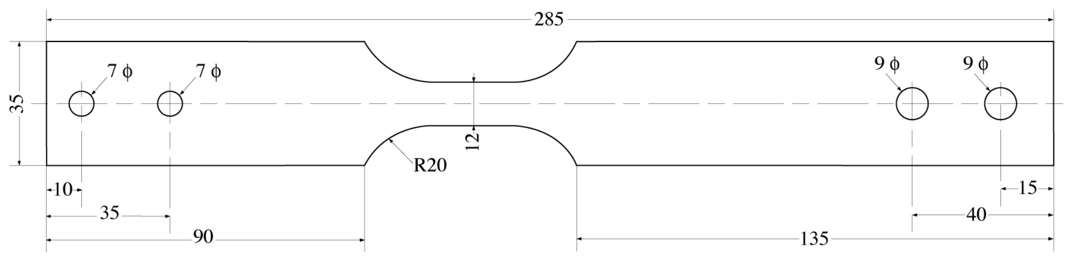


Figure 10 Specimen used by ThyssenKrupp Stahl

Appendix V

Improvement of Data Quality for One Bar Method (Nippon Steel Corporation)

Phenomena

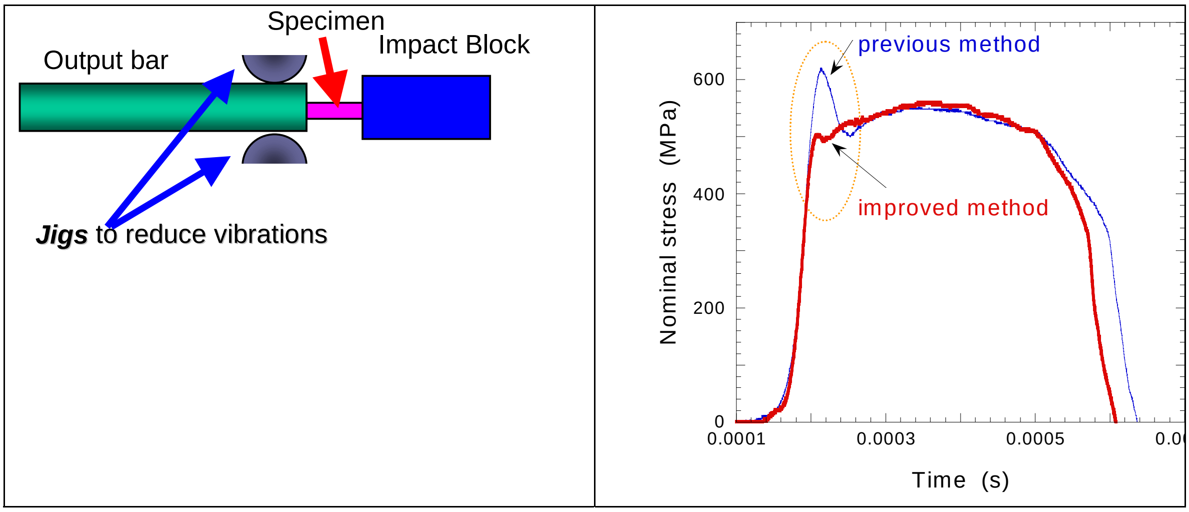
In many cases, , initial peaks around yield point are recorded during tensile tests at high strain rates.

Origins

Pseudo initial peaks are caused by micro-vibrations of the output bar at the interface with the specimen. They are possibly induced by the bending of the output bar by gravity and/or the misalignment of the impact block along the tensile direction.

Improved configurations of the test system

The alignment of the output bar, the specimen and the impact block should be strictly kept along the tensile direction. In addition, it was shown that jigs near the interface between the bar and the specimen can prevent efficiently micro-vibrations of the bar.



Conclusions

The alignment of the output bar, the specimen and the impact block along the tensile direction is important. Stress-strain curves measured by the improved machine configuration are free from pseudo initial peaks.