Tensile Test Curve Nonlinearity

Identifying and resolving common causes of test curve nonlinearity and other curve quality problems

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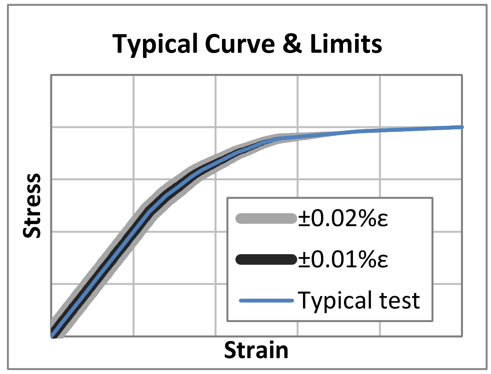
Nonlinearity in the stress-strain curve has many causes and can be difficult to diagnose. These problems are often misdiagnosed as extensometer performance problems or "slippage". This technical note covers some of the most common problems which cause test curve nonlinearity and other curve quality issues.

Is the extensometer accuracy just out of spec? Probably not.

Most Epsilon extensometers are specified to meet ASTM E83 class B-1 and ISO 9513 class 0.5 accuracy requirements – at 15mm gauge length, that's ±0.01%ε for small strains. At right we see the range of indicated test results for an extensometer exhibiting up to *double* this variation.



> *Most test curve linearity and quality problems are related to the test method and execution and do not indicated out-of-spec device performance, which is generally not even observable on a stress-strain graph.*

Differential diagnosis

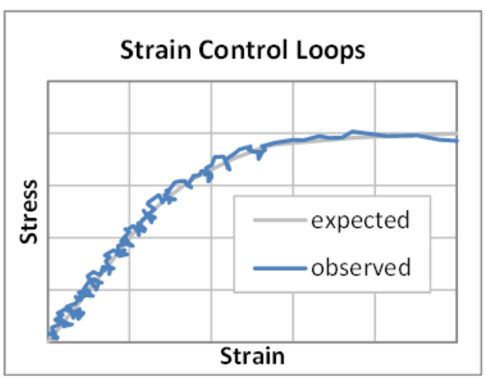
Some of the common causes are easily identified by visual assessment, so this is a good place to start.

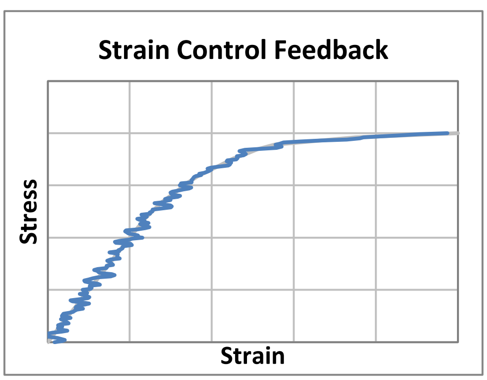
Strain control problems – address these first

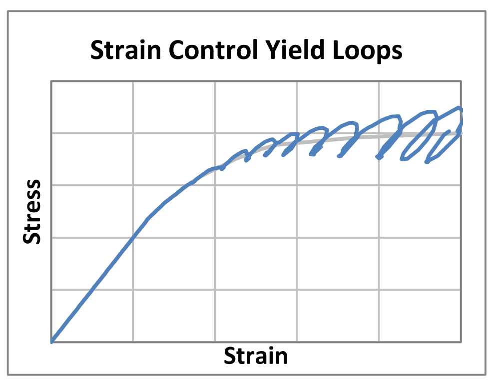
Strain control tuning is a common source of trouble and can manifest in a variety of ways as shown below. The first step in troubleshooting any such problem is to rule out the effects of strain control tuning problems by repeating the test in load- or displacement-control.

> *Strain control problems may be exacerbated by a variety of issues such as vibration, system alignment, and specimen properties. Many applications are simply unsuitable for strain-controlled testing.*

See www.epsilontech.com/tech-notes for more detailed help on this advanced topic.







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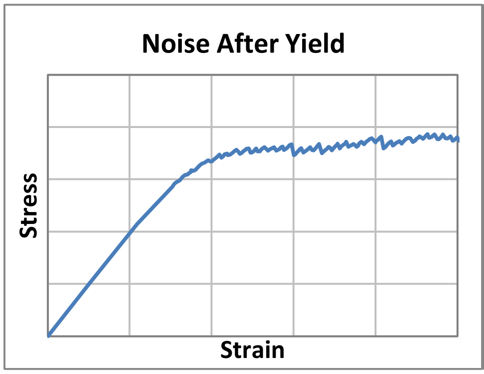
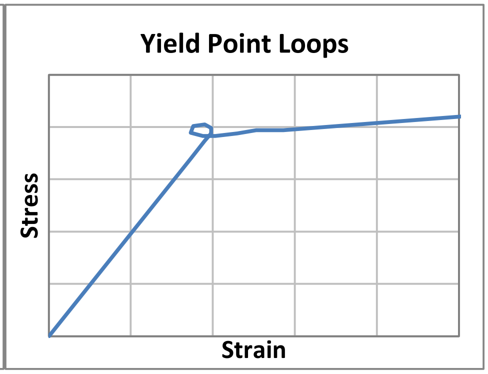
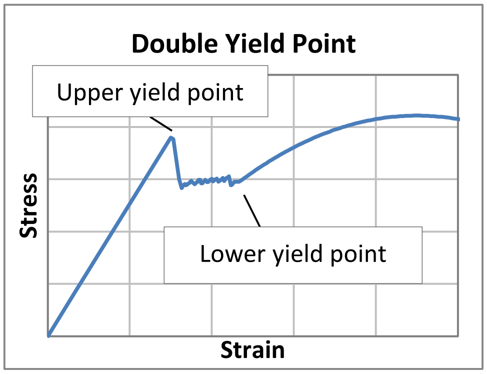
Nonuniform materials

Some materials innately exhibit nonuniform deformation behavior such as discontinuous yielding, serrated yielding, and Lüders bands. These common phenomena can cause noise after yield, double yield points, and reversing load and/or elongation at the yield point (loops), especially if yield occurs outside the gauge length of the extensometer. When combined with strain control, strain control yield loops may occur. If sometimes undesirable, these phenomena are usually real material behavior, not measurement errors.

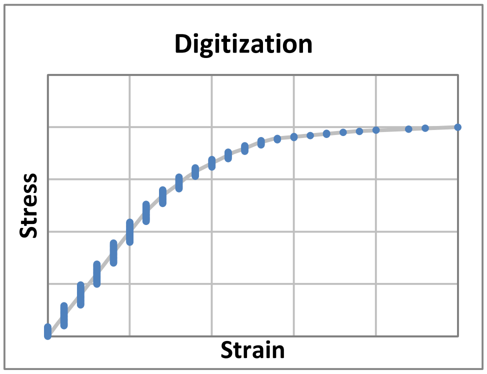


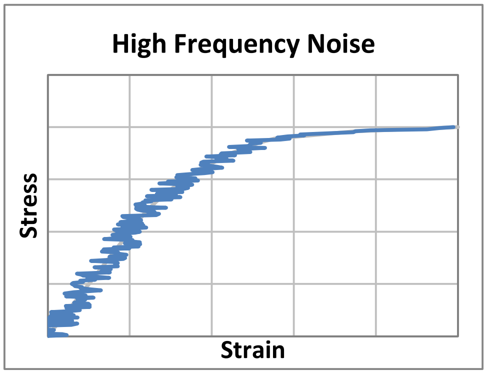




Data collection and interpretation

Two common problems relate to data collection. Digitization (discretization) of stress and/or strain results in "stair-steps" in the test data. This problem generally occurs due to rounding in the user's software or test method; strain-gaged extensometers themselves are analog devices, not digital.





High-frequency or random measurement noise with no visible characteristic frequency may be due to low quality or inappropriately configured data acquisition(DAQ) systems. This is very common in R&D settings.

The measurement resolution of strain-gaged extensometers is extremely good, and resolution is generally limited by the DAQ itself. A typical DAQ will achieve a noise level of 1/20,000 to 1/100,000 of the full scale range of the extensometer.

> ⚠ *Noise will be proportionally larger as the gauge length and measurement range are reduced. Is your test method appropriate?*

See www.epsilontech.com/tech-notes for additional tech notes on *resolution and noise*. Capacitive and optical devices may have less basic resolution – check the listed resolution of the instrument. *Note that all noise sources in this category are consistent between tests.*

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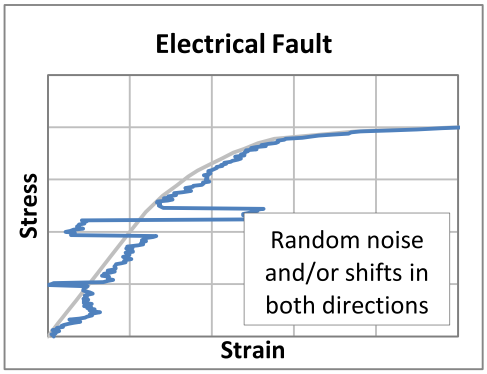
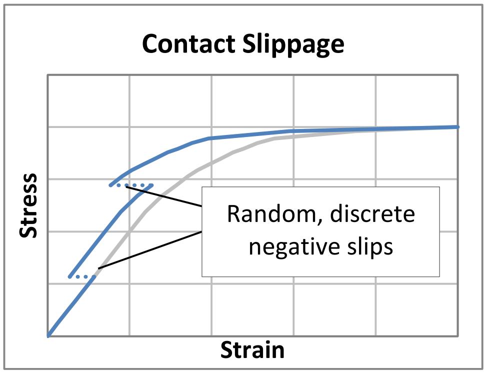
Electrical faults



Impending extensometer failure is most often characterized by random noise and/or very large random shifts in strain in both directions. The noise is typically wandering and random, and may be intermittent or highly variable between tests – a notable distinction from the high frequency random noise covered on the previous page. Electrical faults are most often caused by physical damage to the signal cables; moving the cables can cause significant shifts in the signal.

Contact point slippage



Physical slip of extensometer contacts is characterized by random, sudden, negative jumps in indicated strain. To mitigate slipping:

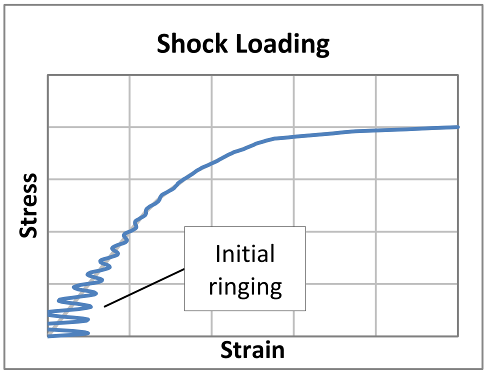
- *Replace dull knife edges / contacts*
- *Use the recommended knife edge / wire form combination . for flat / round specimens (see your user manual)*
- *Use 3-point knife edges when testing flat specimens*
- *Ensure sufficient contact force (adjust wire forms)*
- *Align the extensometer well with the specimen*
- *Seat/settle the extensometer after mounting*
- *Use a longer gauge length (>20mm recommended)*

On a very hard polished specimen, drops of quick-drying glue etc. may be used to create small areas where the knife edges will not slip. Usually this is not necessary. Do Not glue the extensometer to the specimen.

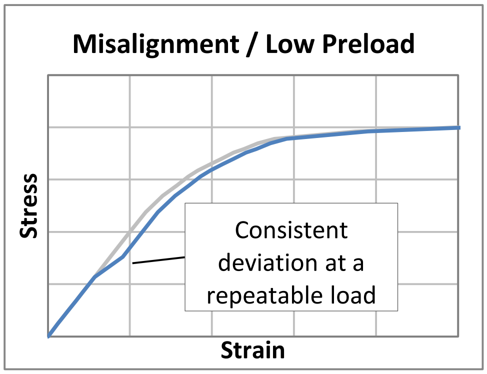
Loading and preloading

> ⚠ *Using a sufficient preload solves many testing problems.*

A variety of problems can result from problems in the test design: specifically, load application. The two problems indicated below can happen in any system but are more common when the load train has mechanical slop, for example with self-aligning U-joints.



If the initial loading rate is too high, the system can be shock-loaded, resulting in 'ringing' in the strain signal due to vibration. Ramp up the loading rate more slowly.



A small perturbation in the curve consistently occurring at a certain load may be caused by excessively heavy grips for a small specimen, especially if the weight of the grips, rods, etc is more than the preload. Increase the preload or improve alignment.

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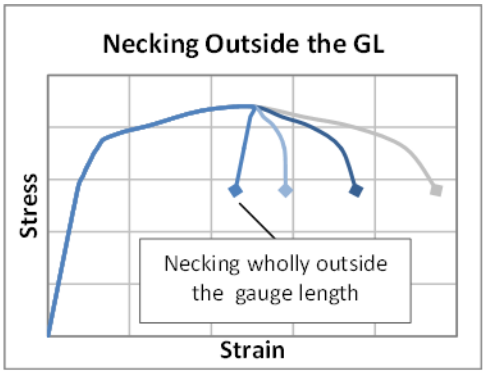
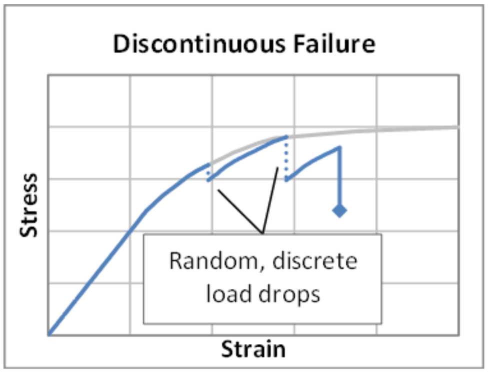
Failure phenomena

For materials which exhibit localized necking (nonuniform plastic deformation) before failure, if necking occurs either partially or wholly outside the gauge length, elongation in the necking regime (*after peak stress*) may be significantly reduced or highly variable. If necking is entirely outside the gauge length, unloading along the elastic line may be observed.

> *This problem is exacerbated if the specimen is straight with no reduced section, or if the reduced section is much longer than the extensometer's gauge length.*





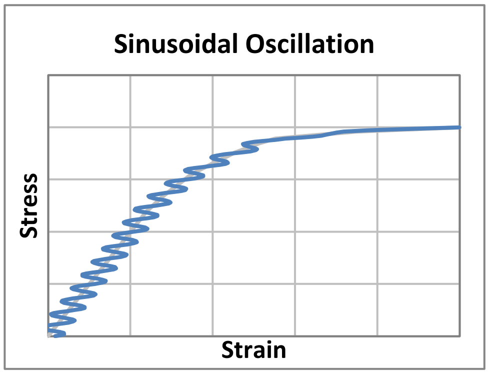
Some materials, particularly composites, are prone to failing through a series of discrete unloading events before final failure. These materials are often *highly* variable between tests after the onset of failure. The unloading events can sometimes be correlated to audible "pinging" as individual fibers fail or de-bond.

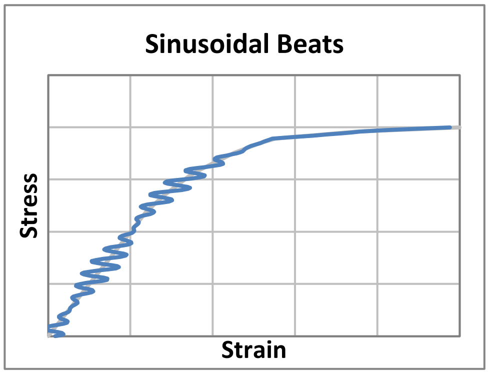
Unloading events may follow an increasing, decreasing, or unchanged strain trend, depending on the nature of the material.

Sinusoidal noise

A variety of sources can cause sinusoidal noise in strain measurement, often related to vibration and dynamics issues. These issues can be exacerbated by strain-control feedback; always eliminate strain-control as a contributing factor when assessing these issues.

Assessment of the frequency content of sinusoidal noise is a key step in its diagnosis and mitigation.





See www.epsilontech.com/tech-notes for more detailed tech notes on resolution and noise.

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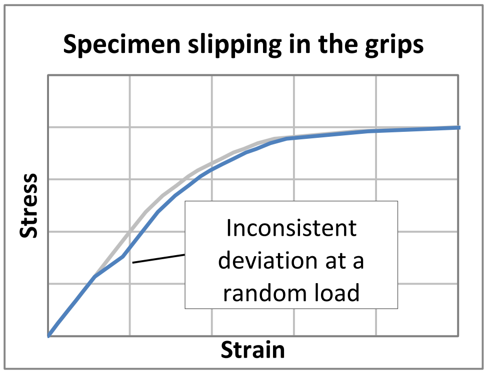
System alignment problems

A wide variety of system alignment problems commonly result in deviations with widely variable characteristics. Most of these problems affect only the elastic region of the test, and are due to real but undesirable nonlinear strains distributed unevenly in the specimen due to bending.



Discrete Specimen slip

Inconsistent deviation / offset at random load from otherwise good curves may be a result of the specimen slipping in the grips. Ensure that the grips are sufficiently tight to prevent slipping, and ensure that specimens are well-aligned and centered in the grips. Use specimen alignment references.

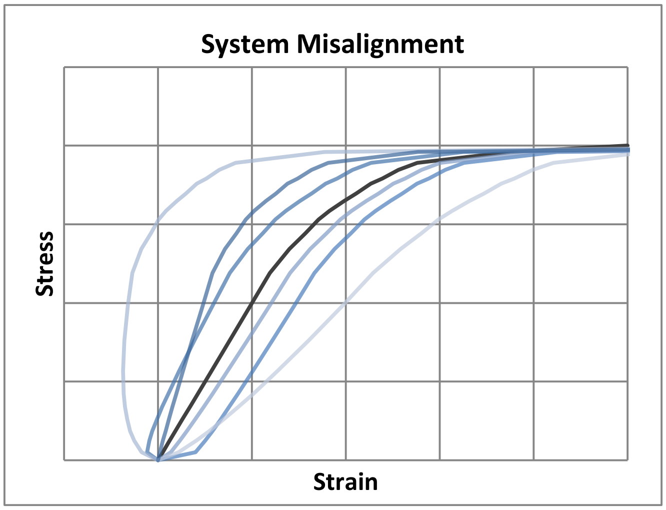
General misalignments

A larger group of problems below are difficult to distinguish. For thin/fine specimens, deviations may be 'taken up' after a small load is applied – use a preload to easily address these. For larger, stiffer specimens, deviations may appear relatively linear (good curves, but inconsistent modulus). Specimens of intermediate size may exhibit highly nonlinear, inconsistent curves which may even go negative.

> *Many of the effects below can be caused by misalignments more subtle than you might expect. Most often these are real but undesirable bending strains - not measurement errors. Use of averaging extensometers (e.g. [3442AVG](3442AVG)) can reduce these problems where elastic modulus is needed.*

Common causes of these problems (shown below) include:

- *Subtle out-of-plane bends in "flat" specimens, especially sheared or flattened specimens*
- *Subtle bend or twist in flat or round specimens, especially if taken off of coil or tube stock*
- *Subtle eccentricity / asymmetry in machined reduced sections of flat or round specimens.*
- *Poor alignment of test specimens with load frame*
- *Subtle misalignment of load frame (grips, rods)*
- *Severe misalignment of extensometer with specimen*
- *Failure to use the recommended knife edge / wire form combination for flat / round specimens (see your user manual)*



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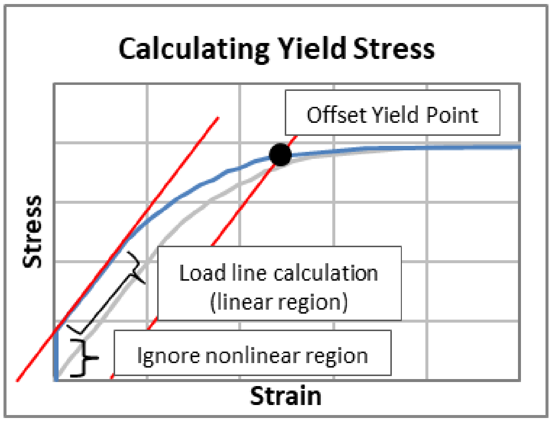
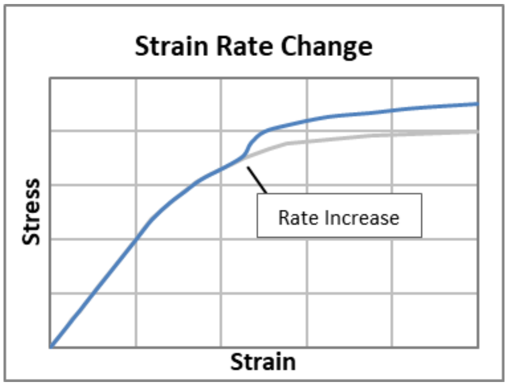
Calculating Yield Strength with Nonlinear Elastic Curves

A wide variety of problems commonly result in deviations in the elastic region of the test as described on the previous page. In some applications it may be more practical to *accommodate* the nonlinearity rather than identifying the source and *mitigating* it. This is particularly useful when the offending region of the test is distinctly identifiable in the test record, even if the cause is unknown.



In such cases, *and regardless of the cause*, a recommended standard practice is to calculate the elastic loading line using the preferred linear portion of the test (*Ref ASTM E8 Appendix X5*). If the initial portion of the test is excluded from the calculation of the elastic loading line, the yield stress calculation may not be impacted by the nonlinearity of the test curve. This method is commonly used to overcome initial test curve nonlinearity.

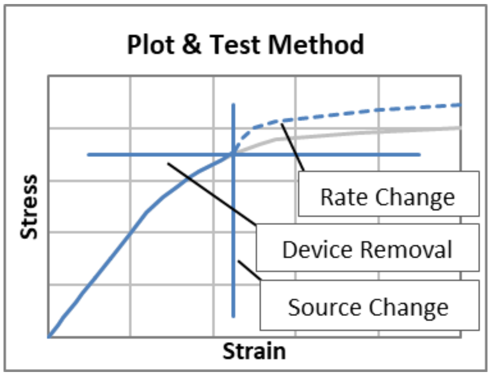
Strain Rate Sensitivity



Tensile test methods often include an increase in the loading rate after yield in order to speed up the latter part of the test while maintaining high data quality in the elastic region. This might be implemented directly as an increase in the specified crosshead speed, or indirectly as a change in control mode (*e.g. from load control to crosshead control*).

Some materials exhibit intrinsic sensitivity to the loading rate. In these cases, a notable step may occur in the test curve at the point of rate increase.

Plot and Test Method Settings



Some common problems relate to the definition of the test method itself, and\or the software settings regarding stress-strain plot. If a tensile test method includes a pause for extensometer removal (but the extensometer output is still plotted thereafter), a horizontal line may be visible. If the strain reading is locked (but the plot continues thereafter), a vertical line may be visible. If the "strain" source is changed to the crosshead after extensometer removal (as an "estimated strain"), and the relation used between crosshead motion and strain does not account for system compliance, then an apparent rate change may be visible, which may or may not correspond to an *actual* rate change.

These artifacts may be present based on the test method definition in software, and some may occur *even if the extensometer is not physically removed*. Often each of these artifacts will begin at the same transition point (as in the example here), but this is not always the case.

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