Fatigue Characteristics of Micro-Measurements Strain Gages

All metals are subject to fatigue damage when strained cyclically at sufficiently high amplitudes; and the foils used in strain gages are no exception. Fatigue damage in a strain gage is first evidenced as a permanent change in unstrained resistance of the gage, ordinarily expressed in terms of equivalent indicated strain, and referred to as "zero-shift". As damage increases in strain gages, cracks eventually begin to develop and these can result in data that is seriously in error.

Micro-Measurements monitors three parameters of strain gages during fatigue life testing: "super-sensitivity", gage factor change, and zero-shift. Super-sensitivity results from cracks that are just forming, and that are open only during the tension portion of the loading cycle. If output of a strain gage is monitored continuously on an oscilloscope during a fatigue test, the waveform observed for an undamaged gage will be a sine wave. As cracking starts, the sine wave will distort during the tension portion of the cycle. Monitoring for onset of cracking is necessary because, at zero load, cracks often close and their presence can be hidden. Experimental stress analysts who unexpectedly encounter large strain signals from strain gages in cyclic applications should check signal waveform for any indications of super-sensitivity.

Fatigue damage in strain gages can also cause gage factor changes, although substantial differences are rare. If cracking has started, however, it will cause an apparent increase in tension gage factor, easily detected because the compression value will be much lower.

Procedures for fatigue testing of Micro-Measurements gages start with the very best installations that can be made (see Appendix A). No strain gage application requirement is more demanding than cyclic endurance. Micro-Measurements uses NAS-942 test rigs with modified beams to achieve strain levels of different magnitudes*. Zero of each gage is recorded along with output for both tension and compression static strains of the same magnitude as will be encountered during cycling. Throughout dynamic loading, gage outputs are monitored for super-sensitivity.

Strain gages can be considered to "fail" over a wide range of damage levels, depending on the application and the required accuracy. For example, in static/dynamic strain measurement, varying with the particular situation, there is some level of damage at which zero-shifts may impair the utility of strain gages for that application. Such zero-shifts thus represent "failure" under those conditions, even though the strain gages could still endure many thousands or millions of additional cycles before fatigue cracks became evident. On the other hand, for purely dynamic strain measurement zero-shift is relatively incidental, and strain gages can be considered functionally adequate until fatigue damage has progressed almost to the stage of super-sensitivity.

Normal behavior of strain gages is illustrated by the following graphs in Figure 1 of data from WK-05-250BG-350 gages. Note that as the strain level is reduced, and life extended, the spread in data increases markedly. Prediction of gage life in high cycle fatigue (over 5×10^5 cycles) is difficult because the test data displays large variations. Using the data in Figure 1, a nominal fatigue life curve can be drawn for WK-05-250BG-350 gages as shown in Figure 2, based on a $100\mu\varepsilon$ zero-shift failure criterion. Other typical data are shown in Appendix B.

Table 1 is a summary of the fatigue characteristics of Micro-Measurements strain gages. "Fatigue Life" in the table generally refers to the approximate number of cycles at which a zero-shift of $100\mu\varepsilon$ can be expected. WD gages, normally used only for dynamic testing, have values for a $300\mu\varepsilon$ zero-shift (approximately).

The data in Table 1 and graphs in Appendix B were obtained using 1/4-in [6.4-mm] gage length strain gages. Gage selection is an important criterion in achieving maximum cyclic life and many different parameters affect the endurance of strain gages. A study of Table 1 will provide information on how the different series (backing/alloy combinations) relate to each other in fatigue life. In addition, a number of other criteria have marked effects and each compromise made deteriorates life to some degree. While there are many aspects to selection of appropriate gages for any application, there are some general "rules" concerning what will improve or deteriorate fatigue life. (Refer to Micro-Measurements Tech Note TN-505, *Strain Gage Selection Criteria, Procedures, Recommendations*.) The larger the grid area of foil strain gage, the higher its fatigue life; but, the higher the gage's resistance, the lower its fatigue life.

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* The NAS-942 beam is designed for constant stress, producing a single $\pm1500\mu\varepsilon$ strain level.

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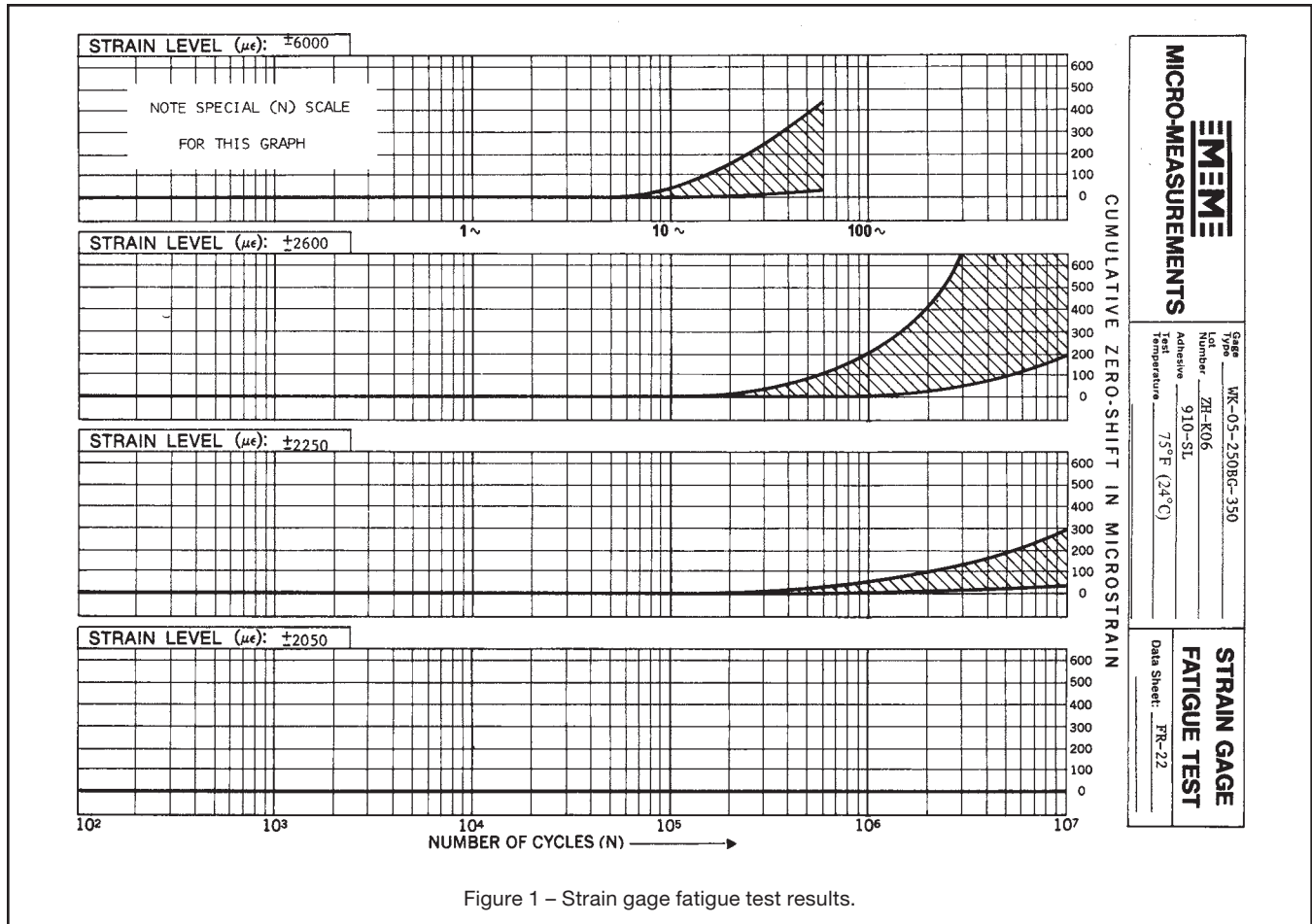

Figure 1 – Strain gage fatigue test results.

Encapsulation (such as 'E' or 'SE' on E-backed gages) is helpful while solder and copper have a negative effect; so CEA-Series gages or gages with Options L, LE, or W on EA-Series gages should be used with caution. Some very small Micro-Measurements gages, and some very high resistance gages, are made using ultra-thin foil. These gages should be avoided where cyclic endurance is important. While such gages can't be identified from catalogs, estimated fatigue life for any Micro-Measurements gages can be obtained from our Applications Engineering Department.
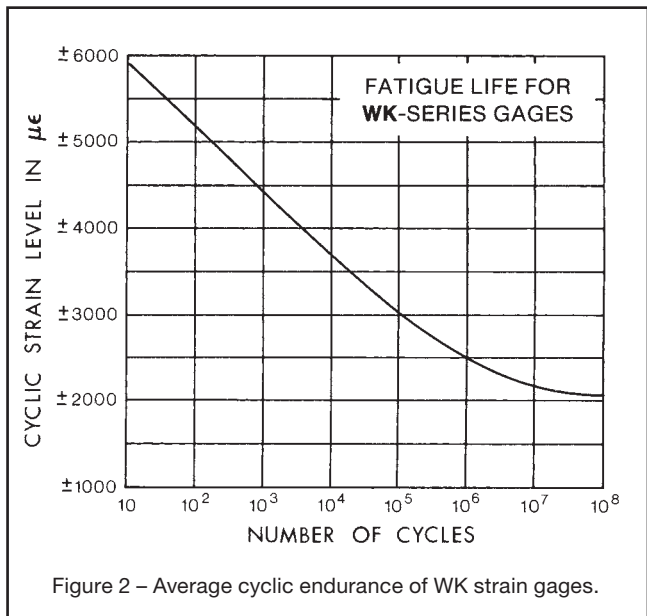

Figure 2 – Average cyclic endurance of WK strain gages.

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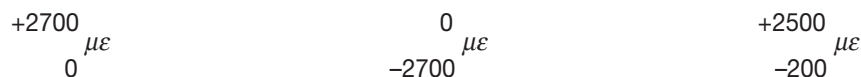
Fatigue Characteristics of Micro-Measurements Strain Gages

Table 1					
Nominal Fatigue Life – 100$\mu\varepsilon$ Zero-Shift					
M-M Gage Series	**Strain Level, $\mu\varepsilon$**	**Number of Cycles**	**M-M Gage Series**	**Strain Level, $\mu\varepsilon$**	**Number of Cycles**
CEA	±1500 ±1300	10^5 10^6	SA	±1800 ±1500	10^6 10^7
EA	±1500 ±1200	10^6 10^8	SK	±2200 ±2000	10^6 10^7
ED	±2500 ±2200	10^6 10^7	S2K	±1800 ±1500	10^6 10^7
EK	±1800 ±1500	10^7 10^8	SD	±2500 ±2200	10^6 10^8
EP	±1500 ±1000	10^2 10^4	TA	±1700 ±1500	10^6 10^7
J2A	±1700 ±1500	10^6 10^7	TK	±2200 ±2000	10^7 10^8
J5K	±2000 ±1800	10^7 10^8	TD	±2400	10^7
N2A	±1700 ±1500	10^6 10^7	WA	±1800 ±1500	10^6 10^7
N2K	±1800 ±1500	10^7 10^8	WK	±2400 ±2200	10^6 10^7
N3K	±1500	10^8	WD	±3000 ±2500	10^{5*} 10^{7*}
*300$\mu\varepsilon$ zero-shift (approximately) for WD strain gages.					

The above fatigue life data is based on fully reversed strain levels. As a generalized approximation, this table can be used for unidirectional strains, or various mean-strains, by taking the indicated peak-to-peak amplitude and derating by 10 percent. As an example, ±1500$\mu\varepsilon$ would be approximately equivalent in gage fatigue damage to strain levels of

$$\begin{matrix} +2700 \\ 0 \end{matrix}\mu\varepsilon \qquad\qquad \begin{matrix} 0 \\ -2700 \end{matrix}\mu\varepsilon \qquad\qquad \begin{matrix} +2500 \\ -200 \end{matrix}\mu\varepsilon$$

A mean-strain which increases in a tensile direction during cycling will lead to much earlier failure, however.

References

"Strain Gages, Bonded Resistance", Classification Specification NAS-942 (National Aerospace Standard 942) 1963. Aerospace Industries Association of America, Inc. Published by National Standards Association, Inc., 1200 Quince Orchard Boulevard, Gaithersburg, MD 20878.

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Fatigue Characteristics of Micro-Measurements Strain Gages

Appendix A – Installation Recommendation for Maximum Strain Gage Fatigue Life

When designing structures for maximum fatigue endurance, special care should be employed to avoid rapid changes in section, stress concentrations, and excess inertial loading, to name a few considerations. When stress concentrations are unavoidable, they should be in a minimum strain field. The same considerations apply to strain gage installations in a fatigue environment.

Ideally, bonding agents used to adhere gages should be unfilled, thin-film-setting adhesives such as M-Bond 200, M-Bond 600 or 610, or M-Bond AE-10 or AE-15. All excess adhesive around the edge of gages should be removed to prevent this unnecessarily thick film of cement from cracking and initiating failure of the gage bond.

Solder connections present the greatest stress concentra–tions at the gage location. Solder is poor in fatigue and, therefore, must be applied sparingly. Controlling solder flow on gage tabs can be accomplished by carefully masking the tab with drafting tape. The masked area should expose a section of the tab only slightly wider than the leadwire diameter. An alternative for limiting solder flow is selection of gages with solder dots and encapsulation. EA-Series gages with Option SE, and SA/SK-Series gages provide very controlled solder masses for leadwire attachment. (Refer to Micro-Measurements Application Note TT-606, *Soldering Techniques for Lead Attachment to Strain Gages with Solder Dots*.) Also, specialty soft solder such as 50-50% Tin-Indium* alloy minimizes stress concentration factors at the solder/tab interface, and will maximize the fatigue life of any user-soldered gage installation. Data presented in this Tech Note for gages without leads was obtained using 63-36.7-0.3% Lead-Tin-Antimony alloy solder (Micro-Measurements Type 361A-20R). This solder is recommended for its ease of use and minimum shrinkage.

All heavy instrument leadwires must be soldered to intermediate terminal strips; terminal strips and gages should be interconnected with small-diameter wires. Proper handling procedures for using terminal strips are described in Micro-Measurements Application Note TT-603, *The Proper Use of Bondable Terminals in Strain Gage Applications*. Any leadwires located in high strain fields should not be rigidly constrained because cyclic stress will fail soft copper wires well before gages fail; a flexible restraint should be provided to prevent peeling of the leadwires and gage tabs from the gage backing. If the strain field at gage locations has been defined, it is good practice to route leads onto solder tabs in the minimum strain direction. After soldering the leads, a flexible restraint should be positioned on them as close as possible to the gage backing. This restraint may be a piece of drafting or aluminum tape (PDT-1 or FA-2, respectively), a small drop of adhesive such as M-Bond AE-10, or a protective coating like M-Coat J.

The WK- and WD-Series, with preattached beryllium copper leads, exhibit the highest fatigue life of any Micro-Measurements strain gages. When using these gages in a cyclic strain field, refer to Micro-Measurements Application Note TT-604, *Leadwire Attachment Techniques for Obtaining Maximum Fatigue Life of Strain Gages*, for the recommended method of leadwire attachment. An EA-Series gage with Option LE should not be used in a fatigue environment.

Most fatigue failures in the strain gage occur in the solder tab and transition area – the area between the tab and the outer gridline. When the strain field has been predefined, it is good practice to position the gage tabs in the lowest possible strain area.

CEA-Series gages may require special attention, although these installations can have the same life as reported for an open-faced EA-Series gage if each installation is carefully made. But some characteristics which make the former gages so convenient for static tests must be carefully managed when maximum fatigue life is required. The large, soft-copper-coated tabs, bonded in the strain field, are subject to cracking at fewer cycles than the high endurance A-foil alone. The act of tinning the tabs can affect the ultimate life of the installation, because solder introduces additional loading on the tabs.

When presented with the large copper-coated tabs of CEA gages, the natural tendency is to apply solder to the entire tab. This markedly deteriorates fatigue life. When cyclic loads are applied to the structure, copper, having lower fatigue endurance than the A-foil, begins to crack. These cracks effectively create notch stress concentrations at the copper and foil interface, which cause the foil to fail prematurely. Solder has greater stiffness and even poorer fatigue endurance than copper; hence, the notch concentration effect may cause even earlier failure of the installation. The encapsulating layer on CEA gages presents a natural solder stop. Adding solder up to the encapsulation creates a stress concentration in the softer copper coating, assuring failure at the encapsulant/solder/copper interface. By placing a minimum amount of solder in only the bottom one-third of the CEA tab area, cyclic life may be markedly improved.

Such solder control may be achieved by masking the solder location with a piece of drafting tape in the lower one-third tab area. This should be followed by the application of a second piece of drafting tape below the first piece, making a gap about the diameter of the solder wire. This exposes a sufficient area of the copper-coated tab for tinning and lead attachment.

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Fatigue Characteristics of Micro-Measurements Strain Gages

Appendix A – Installation Recommendation for Maximum Strain Gage Fatigue Life

Available solders have a variety of characteristics. While melt temperatures are most familiar, solders also vary in their stiffness, shrinkage and their resistance to cyclic loads. The higher the melt temperature, the greater the solder's stiffness and shrinkage. Eutectic solders, regardless of composition, provide for the best cyclic endurance for that composition. The solders listed in Micro-Measurements Strain Gage Accessories Data Book are all eutectic or nearly eutectic, and may be selected based on a given fatigue test's thermal conditions. When the test is to be run below +350°F [+*175°C*], 361A-20R offers the least stiffness and shrinkage. With lower stiffness, less stress concentration occurs at the solder/copper interface; and, the less shrinkage a solder has, the lower the peel stress that is imposed on the tab during solder solidification. When the maximum fatigue life of a CEA installation is required, INDALLOY® 50/50 Tin-Indium solder should be used. This is a very soft solder which melts at +242°F [+*117°C*] and has very low stiffness and shrinkage. The solder requires some practice to apply as its wetting and flow characteristics are poor.

Regardless of the solder chosen, only a minimum amount of solder should be applied to tin the exposed tab area between the pieces of drafting tape.

Soldering iron temperature should be set no higher than necessary to melt the solder being used, as excessively high soldering temperatures may cause the strain gage tabs to lift from the gage backing.

When auxiliary soldering flux is used with (for example) solid solder wire, the flux should be applied sparingly because these fluxes contain volatile solvents that may contribute to tab lifting. Dipping the solder wire into the flux, and then letting the excess flux drain from the solder for a few seconds before wiping the fluxed solder across the gage solder tabs, will normally apply the proper amount of flux. The gage tabs may then be tinned following the procedures outlined in Micro-Measurements Application Note TT-609, *Strain Gage Soldering Techniques*.

Gage-to-terminal wiring may use either solid copper or stranded leads, and should not be larger than 34-AWG [0.0063 in [*0.160 mm*] diameter]. All leads should be supported as close to the solder connection as practicable. This prevents inertial loads from peeling the gage tabs from the gage backing. Our Strain Gage Accessories Data Book lists various types of wires that can be chosen for the intra-bridge connections.

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* Indium solders, available from Indium Company of America, are difficult to apply and expensive.

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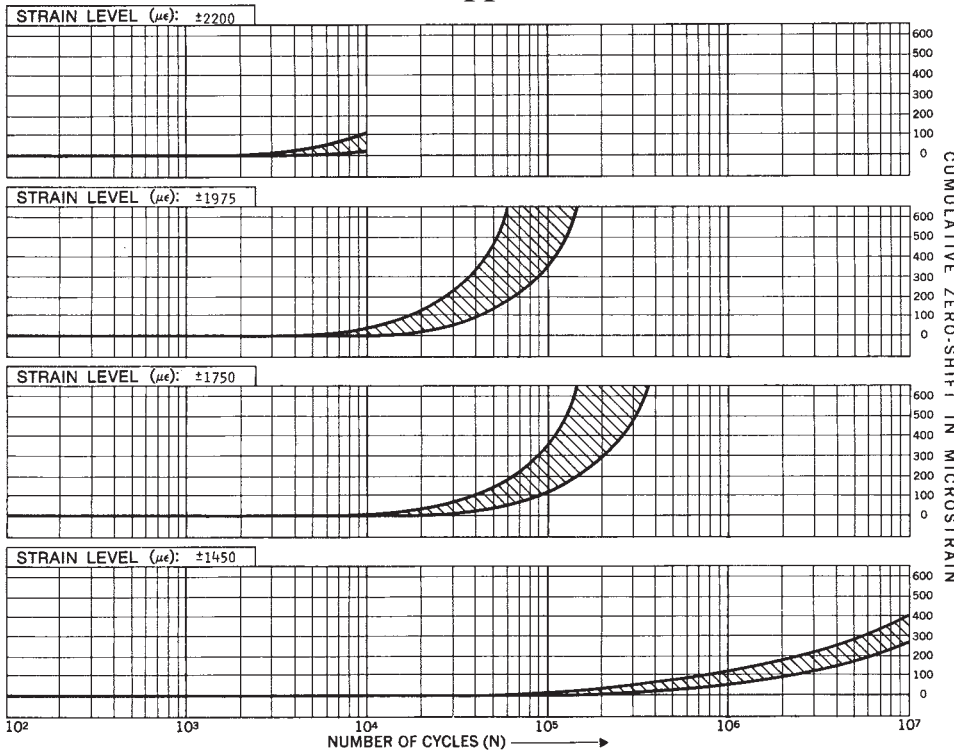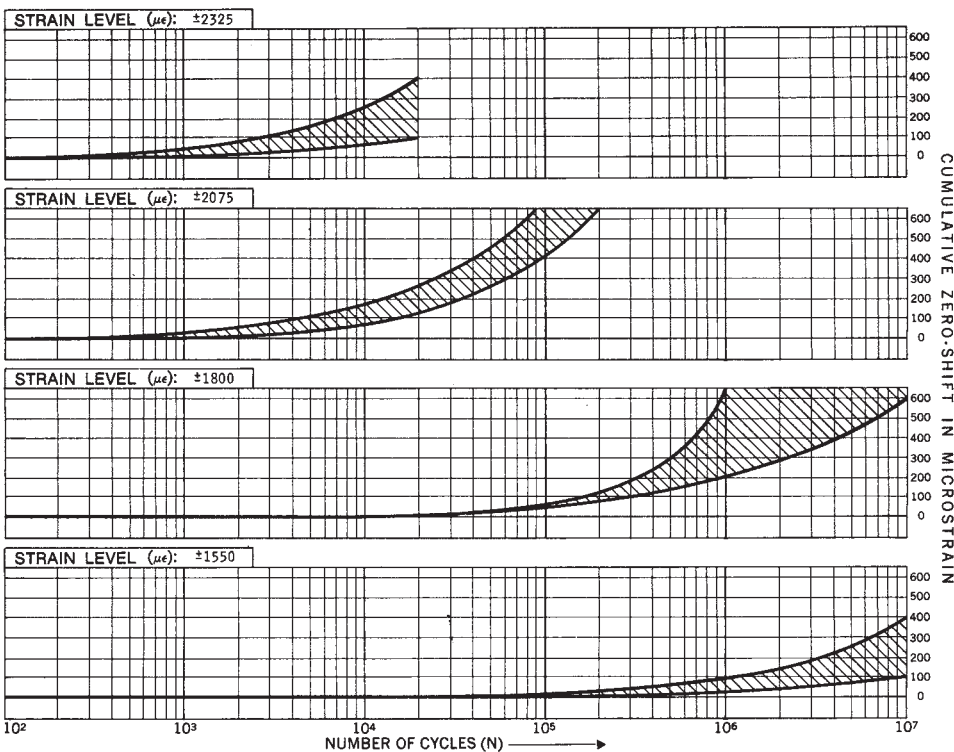
Appendix B

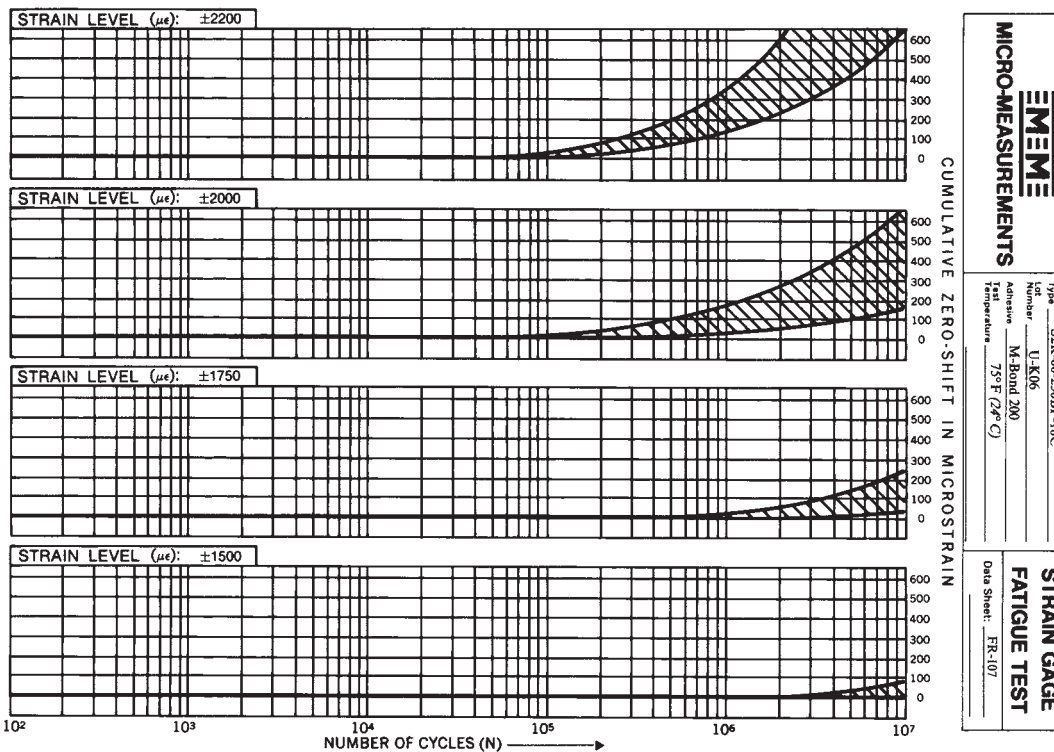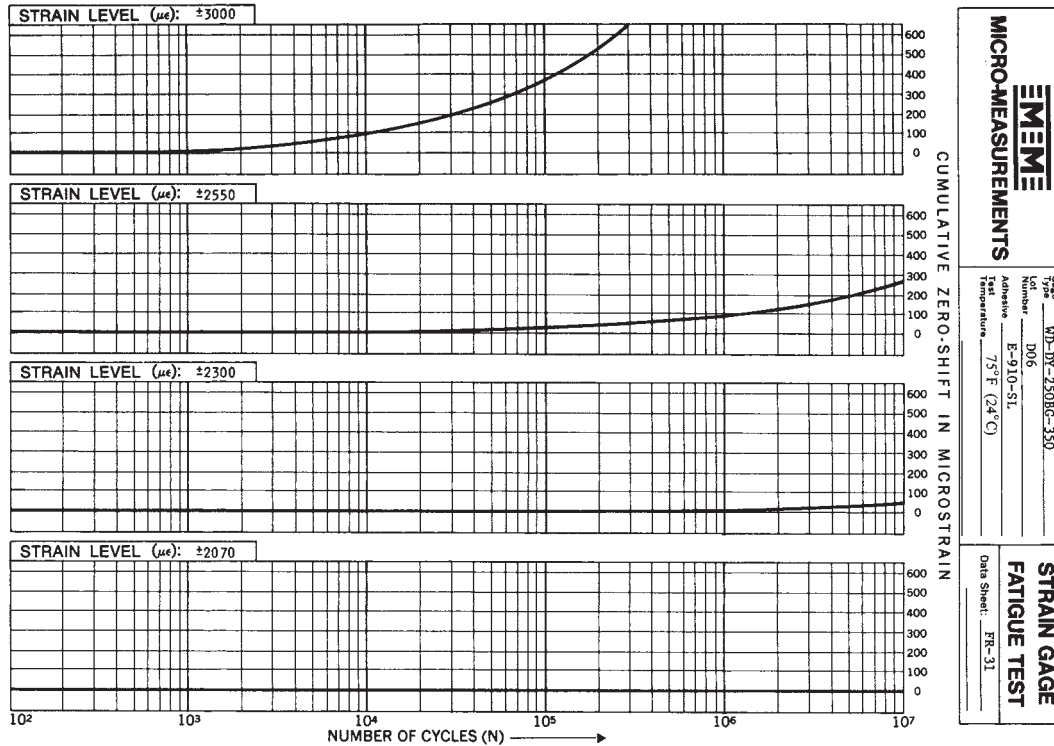VISHAY
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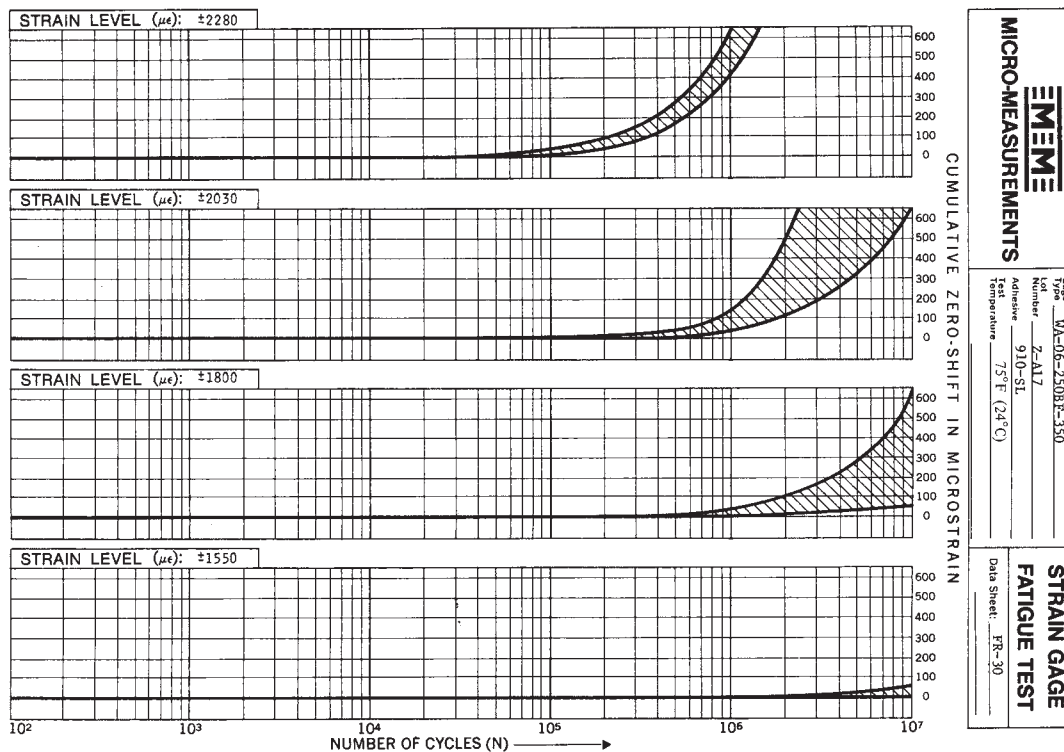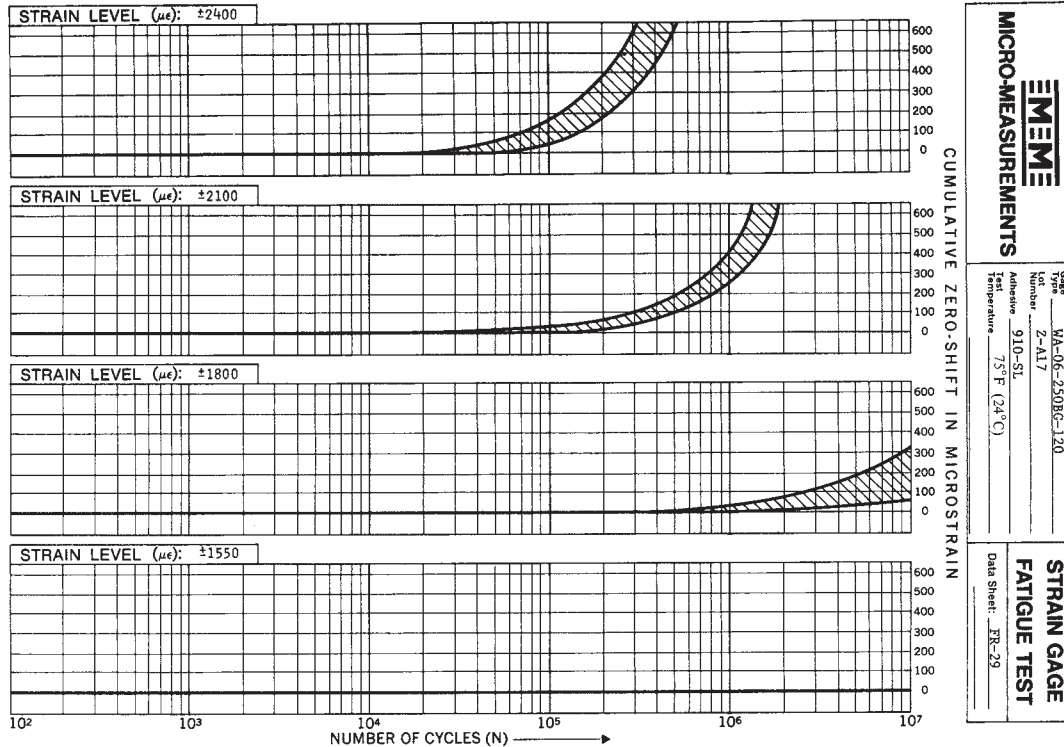
Fatigue Characteristics of Micro-Measurements Strain Gages

Appendix B

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Fatigue Characteristics of Micro-Measurements Strain Gages

Appendix B