Silicon or Foil: Which Strain Gage should be used in Force/ Torque Transducers?

The Future vs. the Past

The semiconductor (silicon) strain gage has revolutionized force sensors since its invention at Bell Telephone Laboratories in the early 1950's. It wasn't until 1960, due to the work of W. P. Mason and R. N. Thurston, that silicon strain gages became commercially available. At that time, it was expected that force/torque transducers using silicon strain gages would obsolete force/ torque transducers using foil strain gages, but change has been slow. Transducers with foil gages are designed near the breaking point in order to get a proper

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output signal, so they have a high failure rate. If the foil gage transducer is made stronger, the output signal will to weak to use. Transducers based on silicon gages are extremely rugged, yet produce powerful signals and allow for a wide bandwidth and short response time. These features are necessary in manufacturing applications due to the harsh environment in which the transducer must operate. This report will compare the benefits of silicon to foil and show why silicon is slowly becoming the strain gage of choice for commercial force/torque sensors.

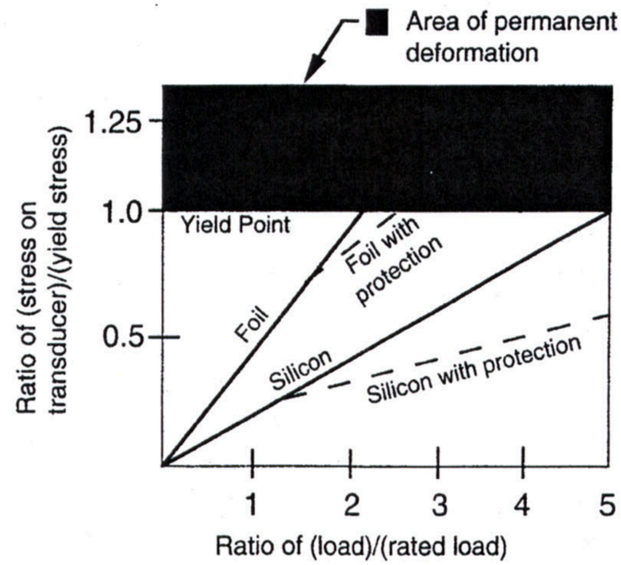

Figure 1. Typical force transducer stress vs. load using foil gages or silicon gages with and without overload protection.

Gage Factor Considerations

Gage factor is a measurement of the sensitivity of the strain gage and is defined as the resistance change per unit of initial resistance divided by the applied strain.

$\Delta R = GF \times R \times \varepsilon$

ΔR: Change in resistance measured to calculate force
GF: Gage Factor
R: Initial resistance
ε: Strain

Foil gages have a gage factor of 2 to 4 while silicon gages have a gage factor of 50 to 175. Due to the low gage factor, transducers using foil gages must be pushed near the yield point to get required output. A high gage factor allows silicon gage transducers to be designed so that the stress at rated load is 5 to 50 times below the yield point. Take care when reading force sensor literature since many manufacturers of foil gage transducers use the tensile strength rather than the yield stress in calculating the factor of safety.

The Problem Of Exceeding the Yield Stress

When a transducer's yield strength is exceeded, the structure is permanently deformed requiring sensor readjustment. This often requires the sensor to be returned to the factory, causing unacceptable lost production time. Production lost due to a broken sensor can far exceed the cost of the sensor. The failure of foil gage transducers in production has even caused some manufacturers to avoid using force sensors on the production line. But the acceptance of silicon gage transducers in the manufacturing environment is now being realized.

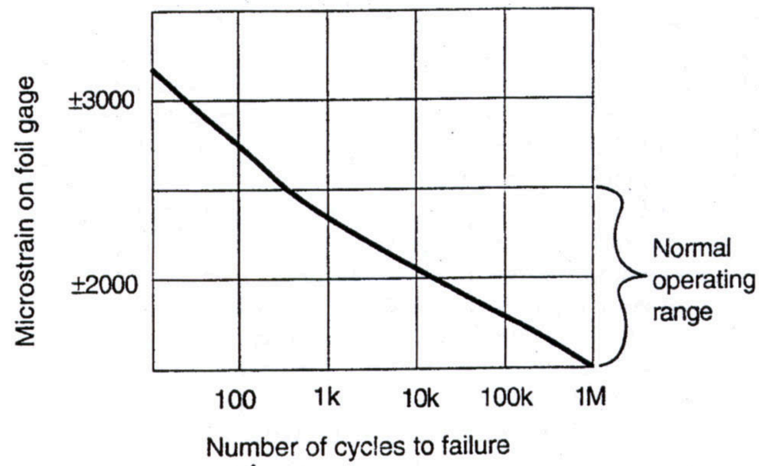

Figure 2. Fatigue life curve for common foil gage, constantan (S-T-C condition).

The Success of Robotic Force Sensing

Robotic force sensors represent a special challenge due to the high and often unpredictable loads applied to the sensor, as well as the high number of cycles involved. Robots are often misprogrammed and crash into objects causing damage to tooling or sensors. ATI Industrial Automation has been suppling robot manufacturers with six-axis force/torque, F/T, sensors based on silicon strain gages. ATI Industrial Automation developed, in conjunction with Adept Technology, an F/T sensor to be used on the Adept robot. Adept Technology, Inc., the largest American robot manufacturer, has been selling this F/T, called Force Sensing Module (FSM), since 1989. Adept has over 300 silicon force/torque sensors in the field, yet there has never been a need to recalibrate or replace a sensor due to a crash or fatigue failure. This type of success has further bolstered the use of silicon gages in force/torque transducers.

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Additional Overload Protection for Silicon Transducers

A technique invented by Thurston Brooks of Hughes STX and used in Adept FSM's increases the already high factor of safety of silicon gage transducers. This technique uses hardened overload pins to protect the transducer. The pins are pressed into the hub of the sensor and float in the outer wall. When the sensor exceeds the rated load, the overload pins contact the outer wall and absorb the additional load. This technique has been tried on foil gage transducers, but has failed since the transducer operates so close to the yield point that when the overload pins start to fully absorb the load the sensor starts to yield. When the sensor yields it is permanently damaged since precise overload pin positioning is critical to successful operation; see Figure 1. Ironically, foil transducers need this overload protection much more than silicon gage transducers, but only silicon gage transducers can use this protection method successfully.

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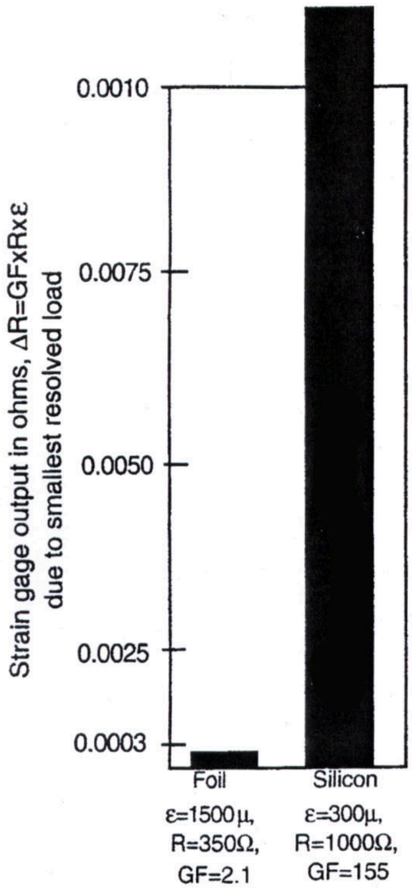

Figure 3. Typical foil and silicon strain gage output due to a load equal to the resolution of a 12 bit A/D converter (1/4096).

Fatigue Life

Fatigue life problems have also plagued manufacturers using force sensors. Since silicon gage transducers have such a low stress point at rated load, they can be designed for infinite life.

Foil gage transducers have two fatigue problems. The first is that the stress on the transducer at rated load results in a limited life span. The second is that the foil gages have limited life spans as well. See Figure 2. A foil gage transducer can fail at anywhere from 100 to 1 million cycles. While this type of performance is acceptable for the research lab, a factory production line can accumulate 1 million cycles on a transducer in a matter of weeks. The Adept FSM has been tested at 150% of rated load for over 25 million cycles with no failure. When the FSM was inspected following this test no sign of fatigue could be found. There are silicon gage force sensors that have over 1 billion cycles in production and show no signs of failure. Only this type of ruggedness is acceptable on a factory production line.

Powerful Output Signal

Considering all the problems associated with foil gage transducers why push them to such a high stress point at rated load? Looking at the change in resistance vs. strain it is easy to see why. Due to the low gage factor of foil gages, strain levels must be from 1500 to 2500 microstrain to produce an acceptable signal. But even at those strain levels the signal is weak, and low-level electrical noise affects the resolution of the sensor. While silicon gages require strain levels of only 50 to 300 microstrain (1/5 to 1/30 the strain on foil gages), they still produce signals that are 35 times stronger than foil gages. Force sensors typically use 12 to 16 bit A/D converters to produce high-resolution digital signals. A force sensor using a 12 bit A/D converter resolves rated load of 1:4096. To achieve this resolution a force sensor using foil gages must resolve 0.00027 ohms, which is difficult. See Figure 3. To make matters worse, induced electrical noise can mask this small change in resistance. Transducers based on silicon gages produce a strong signal output with high electrical noise immunity.

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Higher Bandwidth

The use of filtering can reduce induced electrical noise to acceptable levels on most foil gage transducers; however filtering reduces the bandwidth and response time of the transducer. New applications in production such as deburring, polishing and drilling require a wide bandwidth output with fast response time. When silicon gages are used filtering requirements are reduced allowing for wide bandwidth and extremely fast response times. Transducers using silicon gages have made demanding automated applications like deburring possible.

Change In Output with Temperature

One shortcoming that strain gages have had is a shift in output with change in temperature (ΔT). There are two different temperature-related problems. One is that the resistance of the strain gage changes with ΔT and the other is that the gage factor changes with ΔT. A change in gage resistance due to ΔT causes a zero shift. A change in gage factor due to ΔT causes a span or gain shift. Silicon gages have a larger span shift than foil gages. Foil and silicon gage's zero shift is similar due to the use of the Wheatstone bridge.

Temperature Problem Solved

The zero and span shift temperature problem has been solved using a variety of techniques. Recently, ATI Industrial Automation has developed a simple correction method for silicon strain gages that reduces the change in output due to temperature to near zero. Regardless of the type of gage used, temperature effects ultimately depend on the type of compensation method used.

Linearity and Hysteresis

The accuracy of a force sensor is directly related to the linearity of the strain gage. The linearity of silicon gages is equivalent to the linearity of foil gages due to the low strain levels needed. Hysteresis is related to the amount of epoxy and plastic between the strain gage and the transducer. Foil gages use a plastic backing along with an epoxy film to mount them to the transducer. The plastic backing causes creep and hysteresis. Silicon gages are mounted directly to the transducer with epoxy. A new silicon gage mounting method uses a micro coat of epoxy that reduces hysteresis even further.

Conclusion

Force/torque transducers using foil gages have a poor reputation for reliability in the tough manufacturing environment. Many manufacturers have avoided using foil gage force/torque sensors due to their poor durability. The new silicon strain gage is the advancement needed in force/torque sensors for the manufacturing production line. Transducers with silicon gages have a low noise output, a rugged design, and a high sampling rate. This can be seen with Adept Technology's six-axis Force Sensing Module and the many other manufacturers who have come to rely on silicon gage force/torque sensing on the production line. The best example of silicon gage force/torque transducer ruggedness was the recent crash of an Adept robot. The Adept robot had an ATI Industrial Automation multi-axis force/torque sensor with tooling attached. The robot was misprogrammed causing the tooling to crash at high speed. The impact was so severe that the tooling was sheared in half—the operator was amazed when he discovered the force/torque sensor was undamaged.

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