

# Packaging of Micro Strain Sensors

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### Abstract

This paper presents results of studies on the packaging of micro strain sensors attached to a stainless steel base as a module and techniques of rapid attachment of sensor modules to substrates to be measured. Strain coupling from the substrate to the sensors using different packaging designs and processes can either enhance or attenuate strains experienced by the sensors. Analytical models were developed to predict the enhancement and transmission loss from the packaging materials and processes used. Experiments were carried out with results verifying that the analysis is accurate to a few percentages of assumed properties. Rapid bonding techniques were developed, which combine spot welding and adhesive bonding with selected bonding materials, to bond pre-packaged sensor modules to substrates in 30 seconds instead of hours as in conventional methods.

### Keywords

Strain sensor, Packaging Strain enhancement, Strain transmission

### INTRODUCTION

For high-performance strain sensors, the signal strengths are prone to degradation or interference by improper packaging design and materials used [1]. Therefore, packaging is a critical consideration in overall sensor applications. Furthermore, some field applications require fast sensor attachment with little or no high temperature curing. A rapid bonding method is needed to bond packaged sensor modules to targeting substrates in seconds. This paper presents a novel packaging design, by locating the sensor on the weaker part of the base structure, which experiences a larger strain than the rest of base structure, resulting in a strain enhancement. On the other hand, each layer of packaging materials will deform under shear stress, which will reduce the strain transferred from the substrate/specimen to the strain sensor, resulting in strain reduction seen by the sensor. Studies of strain transmission will assist future packaging design and modular integration.

### Fast bonding

In order to reduce required bonding time for sensor attachment, a fast bonding technique was developed. Metal foil strain sensor was first bonded onto a patterned stainless steel foil by using conventional strain gage adhesive and cured at an elevated

temperature, which served as a prepackaged sensor module. Fast-cure (in seconds) adhesive is then applied on the center portion of package's backside, attached onto a desired substrate and followed by spot welding on both ends. This process can greatly reduced bonding time from hours to 30 seconds. The welding provided a good shear strength immediately; the adhesive reduces the fatigue and buckling problems over long life time.

### Strain enhancement

As shown in Figure 1, a metal foil strain sensor is mounted on a stainless steel foil with an opening in a section, where the sensor is to be mounted.

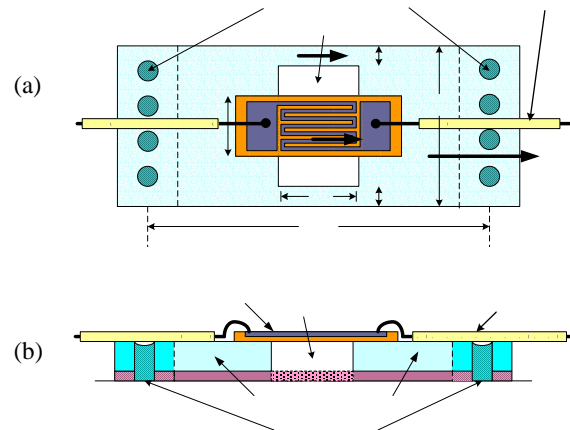


Figure 1. Schematics for strain enhancement testing (a) top view (b) cross-sectional view

Assuming the stainless steel base is adhered to the steel substrate with spot-welded on both ends. Force applying on the base is

$$F_b = \sigma_b A_b = (E_b \cdot \epsilon_b) \cdot W_b \cdot t \quad (1)$$

where  $\sigma_b$ ,  $A_b$ ,  $E_b$ ,  $\epsilon_b$ ,  $W_b$ , and  $t$  are stress, area, Young's modulus, strain, width, and thickness of the stainless steel base, respectively. The force applied on the upper ( $F_{e1}$ ) and lower ( $F_{e2}$ ) slots can be expressed as

$$F_{e1} = (E_b \cdot \epsilon_{e1}) \cdot W_{e1} \cdot t \quad (2)$$

$$F_{e2} = (E_b \cdot \epsilon_{e2}) \cdot W_{e2} \cdot t, \quad (3)$$

where  $E_b$ ,  $\epsilon_e$ ,  $W_e$ , and  $t$  are Young's modulus, strain, width, and thickness of connecting beams, respectively.

If  $W_{e1} = W_{e2} = W_e$ , then

$$F_e = (E_b \cdot \epsilon_e) \cdot W_e \cdot t \quad (4)$$

(A) When no sensor is placed on the stainless steel base, the force applied on the base is equal to the force applied on the thinned parts,  $F_b = 2F_e$ ,

$$(E_b \cdot \varepsilon_b) \cdot W_b = 2 \cdot (E_b \cdot \varepsilon_e) \cdot W_e \cdot t \quad (5)$$

From Equation (5), the strain enhancement factor from packaging will be:

$$\frac{\varepsilon_e}{\varepsilon_b} = \frac{w_b}{2w_e} \quad (6)$$

(B) With sensor attached to the package, the force applied to the package will become equal to the force at the thinned parts and the force applied on the sensor,

$$F_b = 2F_e + F_s \quad (7)$$

The highest strain in the base is located at the weakest part of the base (at  $L_s$ ) since metal foil is relatively soft in comparison to stainless steel foil. Therefore, strain on the base and the metal foil at the  $L_s$  region will be the same.

Total base displacement is equal to displacements at sensor on the center and both ends of stainless steels, thus,  $(L_b - L_s) \cdot \varepsilon_b + L_s \cdot \varepsilon_e = L_b \cdot \varepsilon_{sub}$ , combining with Equation (7), strain enhancement factor can be derived as

$$\frac{\varepsilon_s}{\varepsilon_{sub}} = \frac{L_b}{(L_b - L_s) \frac{2E_b W_e t + E_s W_s t_s}{E_b W_b t} + L_s} \quad (8)$$

### Strain transmission loss

For high performance strain sensors such as capacitive strain sensor [2], when a strain is applied, deformations of package material will reduce sensor's sensitivity. This attenuation from the package is caused by the mechanical elasticity of bonding/packaging materials. As shown in Figure 2, when a force  $F$  is applied on the steel substrate that causes the strain to be transmitted to the sensor or base through the interface layer,

$$F = \sigma A_{x-section} = V \quad (9)$$

where  $V$  is the shear force on the interface between steel substrate and adhesive. Equations governing the deformation, or strain losses, at the interface layer are:

$$\text{Shear stress: } \tau = \frac{V}{A} \quad (10)$$

$$\text{Shear strain: } \gamma = \frac{\tau}{G_e} = \frac{V}{AG} \quad (11)$$

Displacement due to shear force [3] is

$$d = h \tan \gamma = h \tan \left( \frac{\tau}{G} \right) \approx h \frac{\tau}{G}, \quad (12)$$

where  $V$  is shear force, and  $G$  is the shear modulus of elasticity of the material. The moduli of elasticity in tension and shear are related by the following equation

$$G = \frac{E}{2(1+\nu)} \quad (13)$$

where  $\nu$  is Poisson ratio of the material.

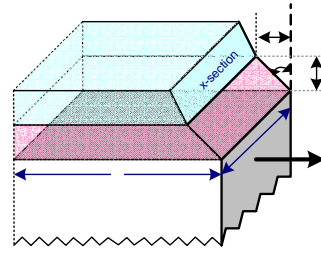


Figure 2. Strain from the steel substrate causes deformation of adhesive and base layers.

Because of the displacement incurred in the interface layer, the strain transmitted to the stainless steel base is less than the strain of the steel substrate—thus the transmission loss or strain attenuation. There are three strain transmission losses in packaging shown in Figure 3, one for each interface layers:

- (1)  $\alpha_1$ : attenuation factor for the adhesive between the stainless steel substrate and steel base.
- (2)  $\alpha_2$ : attenuation factor for the stainless steel base
- (3)  $\alpha_3$ : attenuation factor for the adhesive between the stainless steel base and sensor

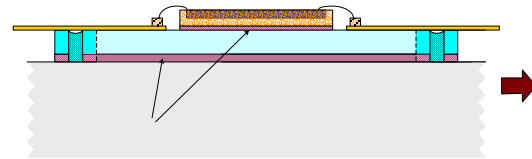


Figure 3. Cross-sectional views of three strain attenuation factors in sensor package

To illustrate the calculation of the strain attenuation factors of each layer, a metal foil strain sensor bonded on a stainless steel base with adhesive was used as an example. The dimension for the 2-mil-thick base is (3 mm×9 mm), thickness for the adhesive is 5  $\mu\text{m}$ , and Young's modulus for the stainless steel is 200 GPa. Assuming the tensile modulus for the adhesive is 6 GPa [4], shear modulus will be 2.31 GPa. With the maximum strain of  $10^{-3}$ , the stress applied from the stainless steel substrate to the stainless base is  $\sigma = \varepsilon \cdot E = 2 \times 10^8 \text{ Pa}$ . The shear force on the adhesive between the base and the substrate will be  $V = F = \sigma \cdot A_x = 30 \text{ N}$ . Two forces will pull the adhesive at both ends; shear stress applied on the adhesive is  $\tau_1 = 2V/A = 2.2 \text{ MPa}$ . The displacement of the base due to the maximum strain of  $10^{-3}$ ,  $\Delta d_1$  can be obtained from  $\Delta d_1 = \varepsilon \cdot l_{adh} = 9 \mu\text{m}$ . The attenuation factor,  $\alpha_1$ , of the adhesive layer can be calculated using Equation (12),

$$\alpha_1 = \frac{d}{\Delta l_{adh}} \approx h \frac{\tau_1}{G_1 \varepsilon \cdot l_{adh}} = 5.291 \times 10^{-4} \quad (14)$$

The transmission factor of the first adhesive layer,  $T_1$ , is  $(1 - 5.291 \times 10^{-4}) \approx 0.9995$ . Similarly, transmission factors for stainless steel base and the adhesive between sensor and base are 0.9999 and 0.9998, respectively.

The overall transmission factor and attenuation factor

are 0.9992 and  $8.2982 \times 10^{-4}$ , respectively. From this calculation, we can neglect this effect in sensor design consideration. However for different height ( $h$ ) and shear modulus ( $G$ ) values of the adhesive used the result would be different.

### EXPERIMENTS ON ENHANCEMENT AND TRANSMISSION LOSS

Experiments carried out in this article all use fast bonding technique for sensor attachment as described below. As shown in Figure 4, the process is described as follows: (a) a metal foil strain gage is pre-attached onto a stainless steel base; (b) an activator (Dymax<sup>®</sup> 535-A) coating is applied to the testing substrate; (c) a fast-fixturing structural adhesive (Dymax<sup>®</sup> 842) is spread on the back of the base with pre-attached sensor using a roller; (d) the base is then attached and secured onto the substrate and pressed with a stamping tool; and finally, (e) the base is spot welded at both ends onto the substrate. Welding was performed on the Unitek model 1-163-03 welding machine with hand piece probe. The maximum power for the machine is 125 mW·sec. A 2% of the full scale (~ 2 mW·sec) was chosen for the welding. The bonding strength for a single spot welding is about 5 N. Each base is welded to the substrate with two rows of 3-4 weld spots on each end. The total bonding process described above does not require high-temperature curing, and the total bonding time can be reduced to about 30 seconds.

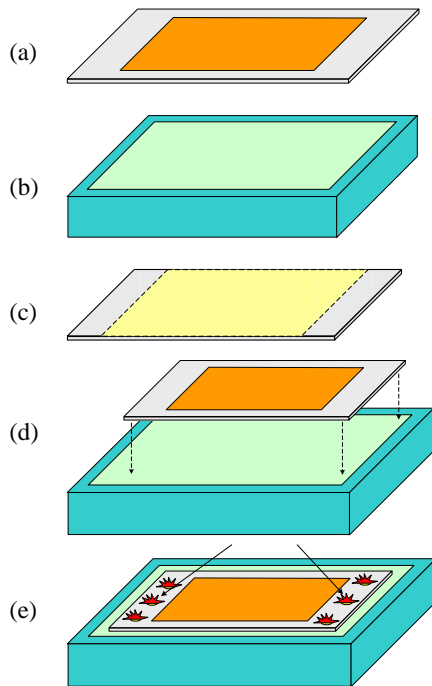


Figure 4. Schematics of bonding procedures (a) pre-attach metal foil on stainless steel base (b) apply activator on substrate (c) apply adhesive on back of steel foil (d) align and attach steel base onto steel substrate (e) spot welds on both ends

Experiments were conducted under a four-point bending beam setup as shown in Figure 5. In strain enhancement experiment, strain gages are mounted on stainless steel bases with and without an enhancement hole. Figure 6 showed a sensor is mounted on a base with an enhancement hole.

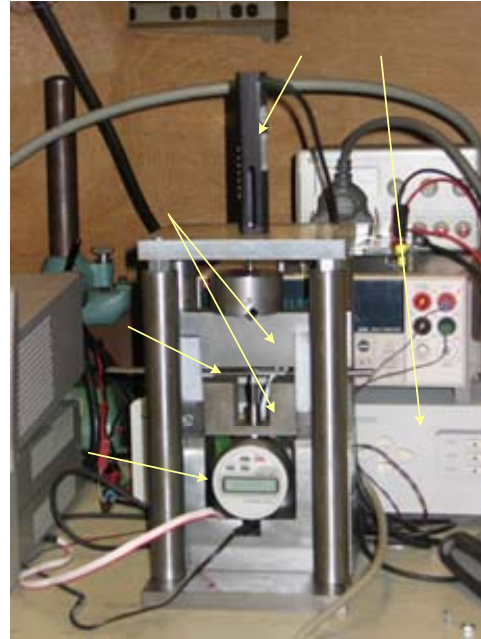


Figure 5. Test set-up for strain sensor testing

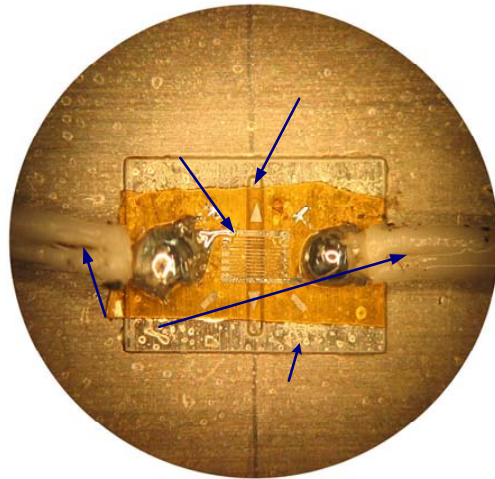


Figure 6. Photograph of a metal foil strain gage mounted on a base with strain enhancement hole.

Testing results are shown in Figure 7, which indicated a strain enhancement factor of 1.32, as compared to the analytical calculation of 1.21 obtained from Equation (8) described in the previous session. The result of the strain transmission experiment, as shown in Figure 8, compares two metal foil sensors bond on steel substrate, (A) without stainless steel base and (B) with steel base between the sensor and the substrate. Then, sensor B has one more adhesive layer than sensor A. The

transmission loss of this additional adhesive layer can be calculated by  $\alpha_i = (GF_A - GF_B) / GF_B$ , where  $GF_A$  is gage factor of sensor without metal base and  $GF_B$  is the gage factor with metal base. By comparing gage factors from the two experimental results, transmission factor of the added adhesive layer can be measured. The value is 0.987, which is close to the predicted value of 0.999 with 1% of error.

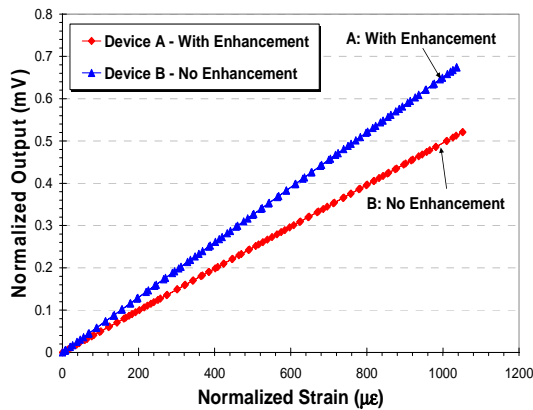


Figure 7. Comparison results for sensors with (A) and without (B) strain enhancement design on base structure.

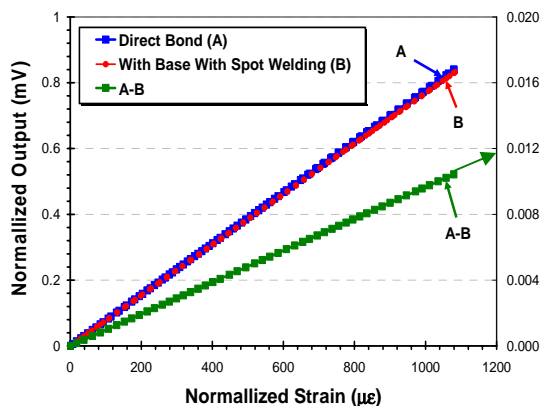


Figure 8. Comparison results for sensors (A) direct bond, (B) bond with the stainless steel base on testing specimen, and (C) difference between A and B (value shown in the second y-axis)

## CONCLUSION

Experiments from this paper showed sensor's sensitivity can be enhanced through packaging design. Strain enhancement factor obtained from package is determined from package's geometry, material, and bonding methods. On the other hand, sensitivity of sensor will decrease due to strain transmission loss, although calculations showed the transmission loss was small, which would not affect metal foil strain sensor much due to its low sensitivity and small stiffness. For high performance MEMS silicon strain sensors, transmission loss results from packaging materials and interface adhesive layers will reduce sensor's sensitivity and should be considered in the device design. This study provides a methodology to quantitatively evaluate strain transmission loss from packaging. Finally, this paper provided a novel method of rapid sensor attachment, by combining fast-cure structural adhesive with spot-welding at selected locations. This method could greatly reduce required time for sensor attachment from hours to seconds.

## ACKNOWLEDGMENTS

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