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AD A 055270

RADC-TR-78-103
Final Technical Report
May 1978

IMPACT STRESSES IN WIRE AND WIRE BONDS: UPPER LIMIT ANALYSIS

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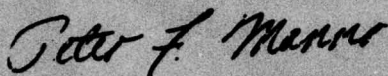Approved for public release; distribution unlimited.

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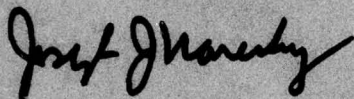
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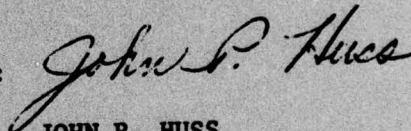
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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER RADC-TR-78-103	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* IMPACT STRESSES IN WIRE AND WIRE BONDS: UPPER LIMIT ANALYSIS.		5. TYPE OF REPORT & PERIOD COVERED Final Technical Report.
		6. PERFORMING ORG. REPORT NUMBER MAE-1229-T-3
7. AUTHOR(s) Charles Libove		8. CONTRACT OR GRANT NUMBER(s) F30602-75-C-0121
9. PERFORMING ORGANIZATION NAME AND ADDRESS Syracuse University 139 E. A. Link Hall Syracuse NY 13210		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61102F 2306J4P2
11. CONTROLLING OFFICE NAME AND ADDRESS Rome Air Development Center (RBRM) Griffiss AFB NY 13441		12. REPORT DATE May 1978
		13. NUMBER OF PAGES 17 P.
14. MONITORING AGENCY NAME & ADDRESS*(if different from Controlling Office)* Same		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

Same

18. SUPPLEMENTARY NOTES

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19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

flat-packs	mechanical screen
stress	wire stress
strain	bond force
drop test	edgewise impact
wire bonds	flatwise impact

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An analysis is made of the stresses produced on a wire bond within a rectangular flat-pack during a flatwise upside-down impact on a rigid floor. The formulas developed imply rather significant wire stresses and bond forces.

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EVALUATION

This program supports RADC TPO No. R5B and was initiated to extend earlier work which evaluated the stresses produced in the lid or base of a rectangular flat-pack by impacts of the package on a rigid floor. This study developed models for theoretically predicting the stresses produced on wires and wire bonds within a rectangular flat-pack by a flatwise up-side-down impact on a rigid floor.

The results of the analysis indicate that an upside-down flatwise drop test of a package can produce wire and bond stresses comparable to those developed in the bond strength tests of MIL-STD-883,"Test Methods and Procedures for Microelectronics." This is significant because it implies that a drop test may have potential as a mechanical screen for wires and wire bonds in sealed packages. This conclusion must be regarded as tentative, however, since the analysis which led to it is critically dependent on the following two main premises:

(a) The impact causes instantaneous arrest of the terminal ends of the wire.

(b) In its subsequent motion, the wire attains a deflected configuration completely devoid of kinetic energy (as in the case of a standing wave vibration).

The non-fulfillment of either assumption will tend to reduce the maximum wire stress and bond force; hence, the formulae developed in the report for the tensile stress and bond force due to a given impact velocity must be considered upper bound formulae.

A more refined analysis should prove extremely valuable to determine to what extent the non-fulfillment of these premises mitigates the maximum wire stress and bond force. This analysis, which can be carried out on the basis of traveling wave theory, utilizing the method of characteristics, is left for a future study. The intent is to study the case of instantaneous or non-instantaneous arrest of the terminals. No assumptions will be necessary regarding the kinetic energy of the configuration of maximum strain energy.

In the event the further modeling bears out the initial promise of the drop test as a screening device, experimental verification of the models will be conducted, as well as some developmental work on the hardware and practical technique of the drop test.

The results of this program will be used by RADC in the development of screening procedures for MIL-STD-883 and in support of the Air Force/NASA task to establish screening requirements for Class S hybrids.

Peter F. Manno

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Project Engineer

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I. INTRODUCTION

Reference 1 studied the stresses produced in the lid or base of a rectangular flat-pack by edgewise and flatwise impacts of the package on a rigid floor, as might occur if the package were accidentally dropped during "normal handling".

In the present report we study the effect of a flatwise upside-down impact on one of the internal components of the package, namely a wire BC with little or no initial slack and terminals at the same level (Fig. 1). In particular, by means of an approximate analysis we arrive at simple upper bound formulas for the maximum tensile stress σ developed in the wire, the corresponding strain ϵ, and the corresponding force F exerted by the wire upon its bonds, all as functions of the impact velocity v.

The main premises of the analysis are that (a) the impact causes instantaneous arrest of the terminals without rebound, and (b) in its subsequent motion the rest of the wire attains a deflected configuration devoid of kinetic energy. A simple energy balance (initial kinetic energy = final strain energy) then leads to the formulas mentioned above.

These formulas imply rather significant wire stresses and bond forces, comparable in magnitude to those developed in the MIL-STD-883A pre-cap pull tests (Method 2011.1 of Reference 2). This is an encouraging result, because it suggests that a flatwise drop test can serve as a mechanical screen for wires and wire bonds in closed packages. However, further analysis is required in order to see to what extent non-satisfaction of the above premises might mitigate the maximum wire stress and bond force. Thus further analysis is left for a future report.

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New York. The helpful discussions with Messrs. Peter Manno, John Farrell, and Edward O'Connell of that Center are gratefully acknowledged.

II. ASSUMPTIONS AND ANALYSIS

A. General.- We assume that the package impacts a rigid horizontal surface upside-down and flatwise, as in Fig. 1, and we neglect any rebound and any flexural deformation of the base to which the wire BC is attached.[*] In that case, the wire may be regarded as a cable that is moving downward with a uniform velocity v and has its ends instantaneously arrested and held at zero velocity.

We shall assume little or no initial slack and let the function $y_o(x)$ in Fig. 2 represent the shape of the wire in its unstrained state just prior to impact. In this state the entire mechanical energy of the wire is kinetic and is given by

$$KE = \frac{1}{2} \rho A L_o v^2 \tag{1}$$

where ρ is the density of the material, L_o ($= S$) the initial length of the wire, and A the initial cross-sectional area of the wire. After impact, the wire will continue moving downward everywhere except at its ends, losing kinetic energy and acquiring strain energy. We assume that eventually a configuration $y_1(x)$ is attained (Fig. 2) that is completely devoid of kinetic energy (i.e., the wire is momentarily at rest everywhere along its length). Neglecting any loss of energy (and the minute change in gravitational potential energy), we may equate the strain energy of configuration $y_1(x)$ to the initial kinetic energy,

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[*]The wires are frequently located near the edges of the package, where the presence of the walls will prevent any significant flexural deformation of the base.

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which is given by Eq. (1), and use this energy balance as a means of determining the state of stress of the wire in configuration $y_1(x)$.

Toward that end, let us denote by F the force that the wire in configuration $y_1(x)$ is exerting upon its bonds B and C. Because of the near straightness of the wire and the additional assumption of negligible horizontal displacements of its elements, we may take F to be the cross-sectional tension everywhere along the length of the wire. This implies that the strain ϵ will also be uniform along the length of the wire.

The strain-energy density (strain energy per unit volume) associated with this strain can be determined from the tensile stress-strain curve of the material (Fig. 3). It is simply the area (shown shaded in Fig. 3) under the stress-strain curve from the origin to the abscissa value of ϵ. Denoting this area by $U(\epsilon)$, we can express the total strain energy of the wire in configuration $y_1(x)$ as

$$SE = U(\epsilon)AL_o \tag{2}$$

Equating this to the initial kinetic energy, Eq. (1), we obtain

$$\frac{1}{2}\rho v^2 = U(\epsilon) \tag{3}$$

as the basic relationship between the impact velocity v and the maximum strain ϵ induced in the wire by the impact.

Equation (3) defines ϵ implicitly. The tensile stress σ associated with this strain is then defined by the stress-strain curve, symbolized by

$$\sigma = f(\epsilon) \tag{4}$$

and the corresponding bond force will be

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$$F = A\sigma \tag{5}$$

B. **Special Case of a Material that Obeys Hooke's Law.-** If the stress and strain are in the linear region OP of the stress-strain curve (i.e., below the proportional limit P in Fig. 3), their relationship is defined by Hooke's law as

$$\sigma = E\epsilon \tag{6}$$

where E is the Young's modulus of the material. The strain energy density then becomes

$$U(\epsilon) = \frac{1}{2}\sigma\epsilon = \frac{1}{2}E\epsilon^2 \tag{7}$$

Substitution of this into Eq. (3) gives

$$\epsilon = v\sqrt{\rho/E} \tag{8}$$

as the relationship between impact velocity and maximum strain developed in the wire subsequent to impact. Equations (6) and (5) then give

$$\sigma = v\sqrt{\rho E} \qquad F = Av\sqrt{\rho E} \tag{9}, \tag{10}$$

for the maximum wire stress and bond force, respectively. These results are of course valid only if ϵ is less than the proportional-limit strain ϵ_p, that is, only for impact velocities satisfying the inequality

$$v\sqrt{\rho/E} \leq \epsilon_p \tag{11}$$

It is interesting to note that σ and ϵ are independent of the span S and the cross-sectional area A of the wire. The bond force F does, however, depend upon A.

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C. Special Case of an Elastic-Ideally Plastic Material.- The tensile stress-strain curve of gold and silver wires in the "hard" temper can be idealized to the form shown in Fig. 4 if one neglects a slight rounding at the knee of the curve. Then for ε greater than ε_p, but less than the fracture strain ε_f, $U(\varepsilon)$ becomes the sum of a triangle and a rectangle:

$$U(\varepsilon) = \frac{1}{2} \sigma_u \varepsilon_p + \sigma_u (\varepsilon - \varepsilon_p) = \sigma_u \varepsilon - \frac{1}{2} \sigma_u \varepsilon_p \tag{12}$$

where $\sigma_u = E\varepsilon_p$ is the ultimate tensile strength of the material. Substitution of this expression into Eq. (3) gives

$$\varepsilon = \frac{1}{2}(\frac{\sigma_u}{E} + \frac{\rho v^2}{\sigma_u}) \qquad \text{or} \qquad v = \sqrt{\frac{\sigma_u}{\rho}(2\varepsilon - \frac{\sigma_u}{E})} \tag{13), (14}$$

as the relationship between impact velocity v and maximum wire strain ε. The wire stress and bond force will be

$$\sigma = \sigma_u \qquad\qquad F = A\sigma_u \tag{15), (16}$$

The above results, Eqs. (13) to (16), depend, of course, on ε being greater than ε_p. Therefore, they are to be used only if Eq. (8) leads to a value of ε greater than ε_p. If Eq. (13) predicts an ε greater than ε_f, this implies that the wire will have fractured in tension as a result of the impact.

D. Special Case of a Material with a Ramberg-Osgood Stress-Strain Curve.- For many materials the stress-strain curve can be approximated very well by the following equation, proposed by Ramberg and Osgood (Ref. 3):

$$\varepsilon = \frac{\sigma}{E} + \frac{3}{7} \frac{\sigma_1}{E} \left(\frac{\sigma}{\sigma_1}\right)^n \tag{17}$$

where σ_1 is a "yield stress", defined as the stress at which the line $\sigma = .7E\varepsilon$ intersects the stress-strain curve $\sigma = f(\varepsilon)$, and n is a parameter that varies from one material to another and is related to the sharpness of the knee of the stress-strain curve. For such materials the strain energy becomes the following function of σ:

$$U = \frac{\sigma^2}{2E} \left[1 + \frac{3}{7} \frac{2n}{n+1} \left(\frac{\sigma}{\sigma_1}\right)^{n-1} \right] \tag{18}$$

and Eq. (3) then gives

$$v = \frac{\sigma}{\sqrt{E\rho}} \sqrt{1 + \frac{6}{7} \frac{n}{n+1} \left(\frac{\sigma}{\sigma_1}\right)^{n-1}} \tag{19}$$

as the impact velocity required to produce any specified maximum wire stress σ. The corresponding strain will be given by Eq. (17). The impact velocity required to rupture the wire can be found by substituting σ_u for σ in Eq. (19). If the ultimate bond strength F_u is known, the impact velocity required to rupture the bond can be found by substituting $\sigma = F_u/A$ in Eq. (19).

III. NUMERICAL EXAMPLE

In order to illustrate the use of some of the above formulas, let us consider a pair of equal strength and equal diameter hard tempered wires, one gold, the other aluminum, having the following characteristics:

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	Gold	Aluminum
Diameter (in.)	.0012	.0012
Area, A (in.^{2})	1.13×10^{-6}	1.13×10^{-6}
Specific Weight (lb/in.^{3})	.7	.1
Density, ρ (lb-sec^2/ft^4)	37.5	5.36
Breaking Strength (grams)	30	30
Ultimate Tensile Strength, σ_u		
(ksi)	58.5	58.5
(lb/ft^2)	8.43×10^6	8.43×10^6
Fracture Strain, ε_f	.02	.02
Young's Modulus, E		
(lb/in.^{2})	12×10^6	10×10^6
(lb/ft^2)	1728×10^6	1440×10^6
σ_u/ρ (ft^2/sec^2)	$.2245 \times 10^6$	1.571×10^6
σ_u/E	4.88×10^{-3}	5.85×10^{-3}

Assuming stress-strain curves as in Fig. 4, we shall then compute the following quantities for each wire: (a) The wire stress σ and bond force F resulting from a 4-foot flatwise drop ($v = 16$ ft/sec). (b) The impact velocity v that would be required to rupture the wire (assuming that the bond can develop the full rupture strength of the wire).

To solve part (a) of this problem, let us tentatively assume that σ will be less than σ_u, so that Eq. (9) is valid. For the gold wire, Eq. (9) then gives

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$$\sigma = 16\sqrt{(37.5)(1728 \times 10^6)} = 4.075 \times 10^6 \text{ lb/ft}^2 = 28.3 \text{ ksi}$$

$$(20)$$

For the aluminum wire it gives

$$\sigma = 16\sqrt{(5.36)(1440 \times 10^6)} = 1.406 \times 10^6 \text{ lb/ft}^2 = 9.77 \text{ ksi}$$

$$(21)$$

Both of these results are below the given ultimate tensile strengths of 58.5 ksi. Therefore the use of Eq. (9) was justified. We note that because of its higher density the gold wire is stressed more severely than the aluminum wire. The bond forces F can be computed as follows:

$$F = A\sigma = \begin{cases} (1.13 \times 10^{-6})(28,300) = .0320 \text{ lb} = 14.5 \text{ grams (gold)} \\ \\ (1.13 \times 10^{-6})(9,770) = .01104 \text{ lb} = 5.0 \text{ grams (aluminum)} \end{cases}$$

$$(22)$$

The wire stresses (20) and (21) and the bond forces (22) are comparable to those that would be developed in the Method 2011.1 MIL-STD-883A pre-cap pull tests (see Fig. 7 of Ref. 4).

To solve part (b) of the given problem, we must set $\varepsilon = \varepsilon_f = .02$ in Eq. (14). Doing this and also substituting the tabulated values of σ_u/ρ and σ_u/E, we obtain the following impact velocity required to rupture the gold wire:

$$v = \sqrt{(.2245 \times 10^6)(.04 - .00488)} = 89 \text{ ft/sec} \qquad (23)$$

The corresponding calculation for the aluminum wire is

$$v = \sqrt{(1.571 \times 10^6)(.04 - .00585)} = 232 \text{ ft/sec} \qquad (24)$$

These velocities would require falls of 122 ft. and 833 ft., respectively,

which are of course too high to be considered normal handling and are likely to cause flexural damage of the base (see Ref. 1).

The bond strength required to develop the full rupture strength of the wire is

$$F = \sigma_u A = (58,500)(1.13 \times 10^{-6}) = .0661 \text{ lb} = 30 \text{ grams} \tag{25}$$

for both the gold and aluminum.

IV.   CONCLUDING REMARKS

The results of the numerical example indicate that an upside-down flatwise drop test of a package can produce wire and bond stresses comparable to those developed in the MIL-STD-883A pre-cap pull tests. This is very encouraging because it implies that such a drop test can be used as a mechanical screen for wires and wire bonds in closed packages.

However, this conclusion must be regarded as tentative, since the analysis which led to it depends critically on the two main premises stated in the Introduction, namely that (a) the impact causes instantaneous arrest of the terminals of the wire, and (b) in its subsequent motion the wire attains a deflected configuration completely devoid of kinetic energy (as in the case of a standing wave vibration). The non-fulfillment of either assumption will tend to reduce the maximum wire stress and bond force; hence the formulas developed herein for σ and F due to a given impact velocity v must be regarded as <u>upper bound</u> formulas.

A more refined analysis is needed in order to see to what extent the non-fulfillment of these premises mitigates the maximum wire stress and bond force. Such an analysis, which can be carried out on the basis

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of traveling wave theory, utilizing the method of characteristics, is
left for a future report. It is intended by means of it to study
the case of instantaneous or non-instantaneous arrest of the terminals
(the latter might be due to base flexibility or the cushioning effect
of the air on the underside of the falling package or the fixture to
which the package is attached). No assumption will have to be made
regarding the kinetic energy of the configuration of maximum strain
energy.

If the more refined analysis referred to above bears out the
initial promise of the drop test as a screening device, some experimental
verification of the theory will be desirable, as well as some developmental
work on the hardware and practical technique of the drop test.

V. REFERENCES

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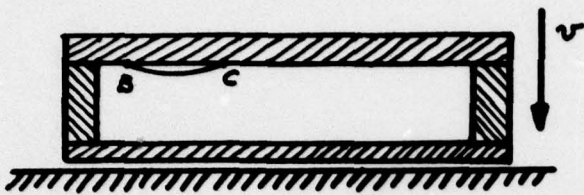   Engineering, Report MAE-1229-T2, September 1977.
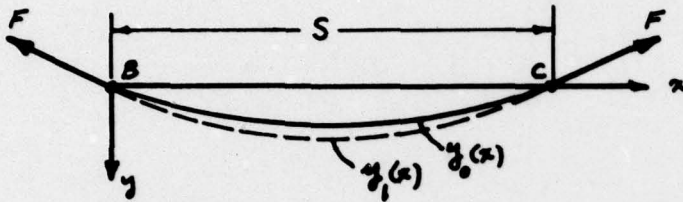
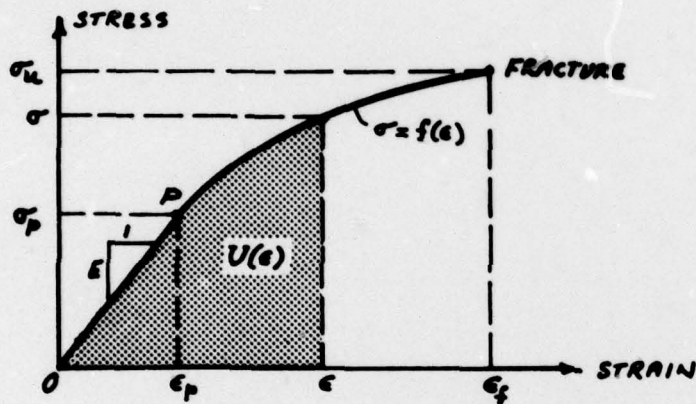FIGURE 1.- Flatwise impact.

FIGURE 2.- Wire configurations.

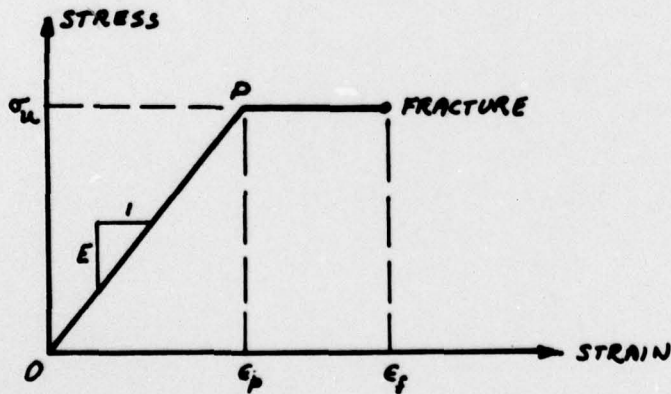FIGURE 3.- Tensile stress-strain curve of a ductile material.

FIGURE 4.- Idealized tensile stress-strain curve for hard-tempered gold and aluminum wires.

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