Enhanced Foam Package Design for Drop/Impact Using Accurate Predictive Simulation

Pengcheng Yin, *Graduate Student Member, IEEE*, Seungbae Park, *Senior Member, IEEE*, Biju Jacob, and Arun Gowda

***Abstract*— The interconnections and chips of the internal components of electronic devices need to be protected to prevent damage during shipping, handling, and daily use. This article studied an investigation into the abilities of foam as an outer packaging material to protect the detector device. This detector device is required to withstand a high-speed impact, 30 mph, and to avoid moisture damage. The finite element model of foam was validated by a compression experiment. The prediction simulation of foam samples was performed by using the validated foam model to obtain the correct stress–strain properties of foam samples. Different shapes, textures, and designs of foam outer packaging were investigated, which include tennis ball shape versus hockey puck shape, inner dimple texture versus outer pimple texture, and monotonic foam layer versus double foam layers. The different foam material combinations of packaging were also compared by using the predicted stress–strain properties of foam in ANSYS/LS-DYNA to study the effect on reducing the out-of-plane deformation of the printed circuit board (PCB).**

***Index Terms*— Foam packaging, high-velocity drop impact, package design.**

I. Introduction

BECAUSE of the increased market demand for electronic items, reliability has become an unavoidable concern. Thousands of investigations have been conducted on the reliability of electronics, particularly in the thermal and shock domains, such as fatigue life experiments [1], thermal/power cycling [2], [3], shock experiments/simulations [4], [5], board-level drop tests [6], product-level drop tests [7], [8], and surface mount technology (SMT) investigation [9], [10]. As the products move from the manufacturer to the final customer, a large amount of impact energy could be delivered at any time to the electronic items. As a result, the performance of the outside packaging of items is critical for preventing product damage. The anti-shock design and shock-absorbing materials of the outer packing should reduce or separate the impact energy from the device, allowing it to withstand harsh environments. Otherwise, the energy could damage soldered connections, causing the product to malfunction. Oh et al. [11] developed a numerical model that showed how a different shape of shock isolator could improve the performance of the shock container. Yu et al. [12] studied the effect of a shield-can attached to the printed circuit board (PCB). They found that a shield-can may mitigate the stress and the out-of-plane deformation of PCB. Foam is widely used in the industry due to its low density and energy absorption properties. For instance, according to Fremgen et al. [13], energy-absorbing foams and other lightweight materials are often utilized in the automotive market to mitigate the forces and stresses on the occupants to protect them during a front or side accident. Shuaeib et al. [14] proved the effectiveness of expanded polypropylene foam as a motorcycle helmet liner owing to its resilience. The finite element method is commonly used for analyzing the drop impact, which can save huge time and cost instead of performing the experiment. In this work, the ANSYS/LS-DYNA was used for simulating the drop impact. ANSYS/LS-DYNA provides hundreds of foam material models that can be applied to the simulation. Sambamoorthy and Halder [15] established a reliable PU foam material model by comparing four different material models in LS-DYNA, namely, low-density foam model, the crushable foam model, Bilkhu-Duboi, and Fu-Chang. Ozturk and Anlas [16] investigated repeated compressive loading and unloading by utilizing the LS-DYNA low-density foam model to forecast the maximum deceleration, force, and displacement for the initial loading.

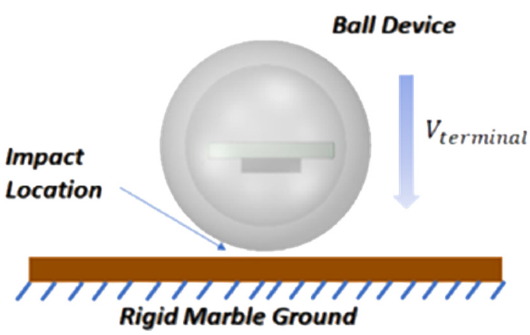

Fig. 1. Schematic of the device drop impact.

In this project, based on the requirement of the company, the detector must withstand a 30-mph impact and be moisture resistant. The schematic of the drop impact of this device is shown in Fig. 1. The closed-cell foam was selected because

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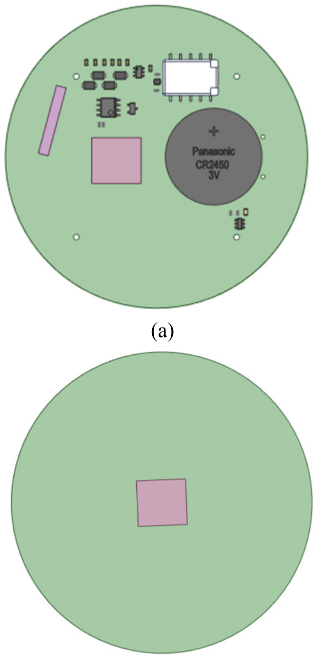


(a)

(b)

Fig. 2. Model simplification. (a) Detailed model of components on the PCB. (b) Simplified model.

TABLE I
MATERIAL PROPERTIES OF SELECTED FOAMS

Material	**Mechanical Properties**	
	Young's Modulus (MPa)	***Density (kg/m³)***
EPDM	0.3	32
Polyethylene	0.8	133.3
PVC	0.6	104.7
Neoprene_1	0.4	92.132
Neoprene_2	1	172.41

TABLE II
MATERIAL PROPERTIES OF THE MATERIAL IN THE SIMULATION

Material	Density (g/cm3)	Young's modulus (MPa)	Poisson's ratio
Battery	2.894	1.93E5	0.265
PCB	2.75	3.2E4	0.28
Ground	2.711	5.4E4	0.3
Polycarbonate tube (Ion sensor)	1.21	2.2E3	0.32
Copper Alloy (Ion sensor)	8.3	1.1E5	0.34
Chip	3.9683	3.9E5	0.27

of all the other impact-resistant foams, it protects against moisture. Several closed-cell foams, such as polyethylene, ethylene propylene diene monomer (EPDM), and polyvinyl chloride (PVC), are easily available on the market. The major aim of the function of the outer packing is to isolate the impact energy to further prevent the deformation of the PCB during drop impact, which might cause electronics reliability problems such as solder crack, chip-cracking, underfill crack, and pad cratering caused by stress and vibration. To reduce the impact energy that is delivered to the PCB, several outer packing configurations, materials, and architectures were investigated in this study.

II. Simulation and Validation of the Foam Model

A. Simulation Setting

The product must survive an impact to the ground at 30 mph according to the requirement. Therefore, the impact velocity is set as 30 mph (13.41 m/s) and the target ground is considered marble ground as the severe impact condition. In this study, instead of implicit analysis, the explicit dynamic integration method was selected in ANSYS/LS-DYNA. The reason for choosing the explicit dynamic method is friendly for the short dynamic response and large deformation simulations which can save a lot of computation time. In the system-level drop impact simulation, to save computation time, some simplified rules were used, such as eliminating some components, modifying the shape of components to a regular shape, and eliminating small holes. In this study, Fig. 2(a) shows the concept of the placement of components, which is not a final layout of the electronic components. Therefore, we need to know the dynamic behavior of bare PCB during impact in order to understand where the electronic components can be placed to avoid server deformation during impact. And by simplification, we can understand the dynamic behavior of the bare PCB and further reduce the out-of-plane deformation of the bare PCB by comparing different designs of foam packaging. The simplified numerical model is shown in Fig. 2(b). As shown in Fig. 2(b), there is only one component placed in the center of the PCB. Therefore, the dynamic behavior of PCB during the drop impact can be extracted and useful information can be obtained based on the results of the drop impact simulation.

B. Foam Sample Characterization

The two types of foam that are commonly available on the market are closed-cell and open-cell foam. Closed-cell foam is stiffer and more durable than open-cell foam because air and moisture cannot enter the material because the cells are tightly packed. The cells are purposefully left open in open-cell foam, though, making the foam softer and more flexible. This characteristic allows air and moisture to pass through the foam. The closed-cell foam, therefore, fully complies with the criteria for moisture resistance. All of the foam that follows, as seen in Table I, is closed-cell foam. The test sample for material characterization and measurements of Young's modulus and density are the foams depicted in Table I. And the following Table II shows the material properties used in the system-level simulation. The MTS Systems Corporation (MTS) compression test vehicle is displayed in Fig. 3. Because the stress–strain curve of the foam model is a required input parameter in ANSYS/LS-DYNA, the compression tests for each listed foam sample were performed. The stress–strain curves of the listed foam appear in Fig. 4.

The finite element approach, which is straightforward, practical, and extremely effective, was used to obtain the proper

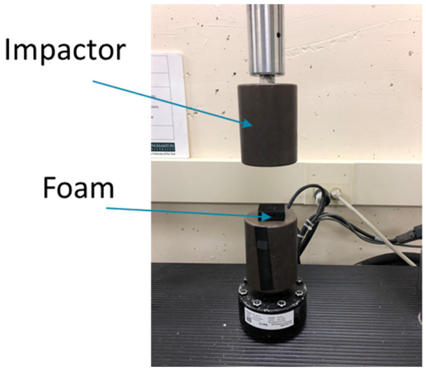


Fig. 3. MTS compression test vehicle.

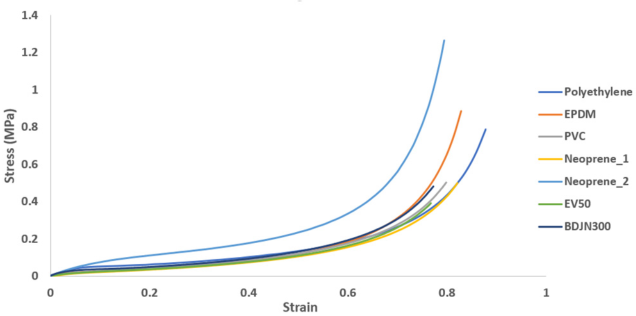
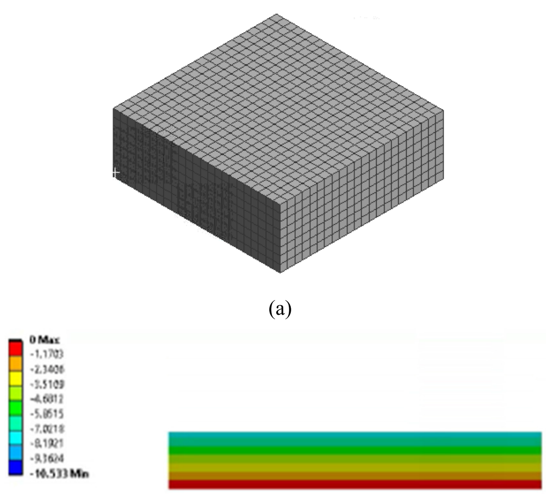


Fig. 4. Stress–strain curves of the listed foam sample.



(a)

(b)

Fig. 5. Finite element model and result of compression simulation. (a) Finite element model of foam sample. (b) Displacement contour of the compression simulation.

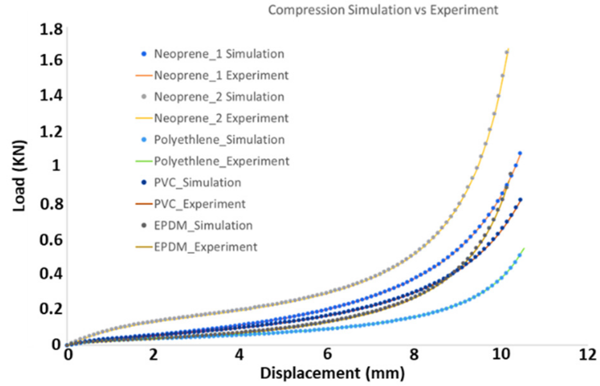
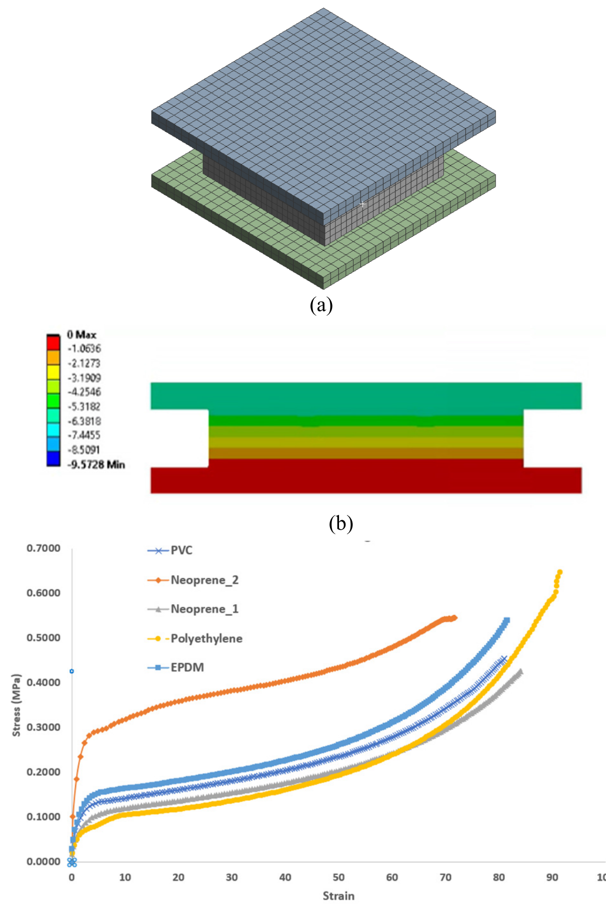


Fig. 6. Simulation results of each foam sample versus its experimental results.



(a)

(b)

(c)

Fig. 7. Prediction foam model and predicted stress–strain curves for each foam sample. (a) Predicted FE model. (b) Displacement contour of prediction simulation. (c) Predicted stress–strain curves of different foams shown above.

stress–strain curve at impact at 30 mph. Because the strain rate keeps changing during drop impact, the correct stress–strain curve should be acquired. To obtain a properly anticipated stress–strain curve, the foam model validation process must come first. In the compression simulation, the upper surface of the foam model was displaced, while the lower surface remained fixed. The displacements are recorded throughout the compression experiment. Fig. 5 shows the model before the simulation.

The force–displacement curves from the compression simulation, shown in Fig. 6, were used to compare the foam materials. The outcomes of all simulations and experiments correlate very well. As a result, the FE models of mentioned foam sample have been verified.

The prediction simulations were run using the verified FE foam model to obtain the stress–strain curve under the 30-mph impact. This was done after verifying the finite element model for each foam sample. Two rigid plates were added to the top

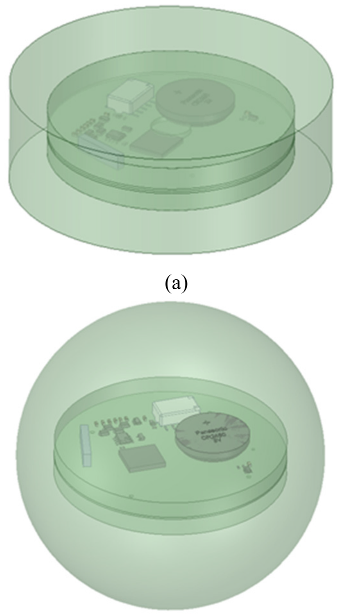


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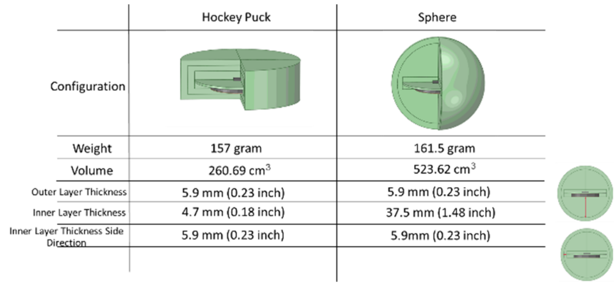
Fig. 8. Numerical model for hockey puck design and tennis-ball design. (a) Hockey puck design. (b) Tennis-ball design.



	Hockey Puck	Sphere
Configuration		
Weight	157 gram	161.5 gram
Volume	260.69 cm^3	523.62 cm^3
Outer Layer Thickness	5.9 mm (0.23 inch)	5.9 mm (0.23 inch)
Inner Layer Thickness	4.7 mm (0.18 inch)	37.5 mm (1.48 inch)
Inner Layer Thickness Side Direction	5.9 mm (0.23 inch)	5.9mm (0.23 inch)

Fig. 9. Design parameters of the hockey puck and sphere structure.

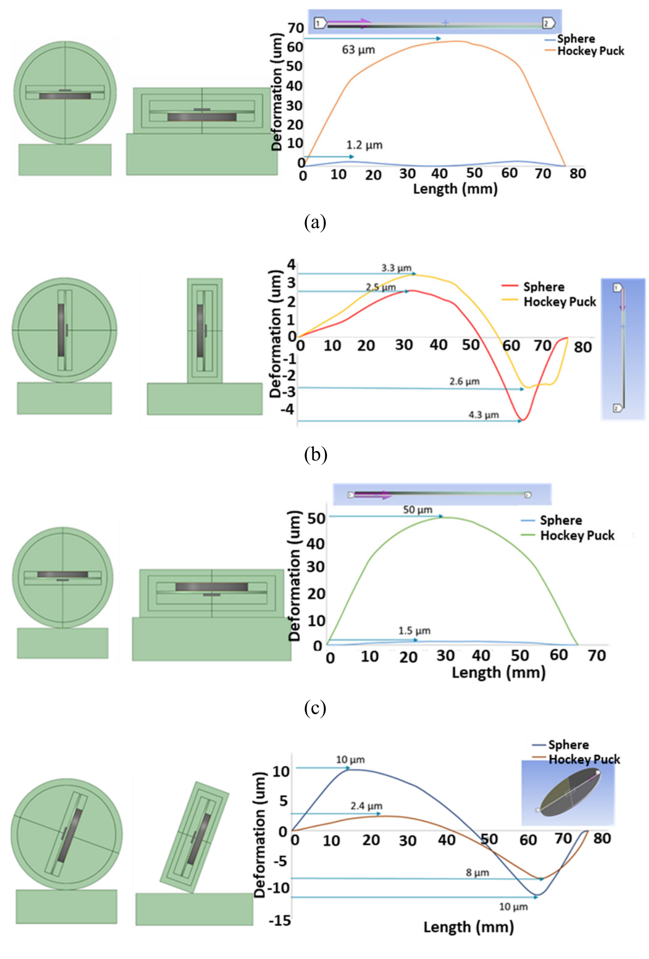


Fig. 10. Simulation results of tennis ball design versus hockey puck design in different drop impact angle. (a) Bottom drop impact: out-of-plane deformation of PCB across the center of the PCB. (b) Side drop impact: out-of-plane deformation of PCB across the center of the PCB. (c) Top drop impact: out-of-plane deformation of PCB across the center of the PCB. (d) Small-angle drop impact: out-of-plane deformation of PCB across the center of the PCB.

and bottom of the prediction simulation to mimic the impact event, as shown in Fig. 7(a). The strain rate of foam material is not constant during the drop impact because the acceleration is constantly changing. Give the top plate (impactor) an impact velocity of 30 mph while constraining the bottom plate in the prediction simulation. Therefore, each foam's stress–strain curve under an impact velocity of 30 mph is represented by the curves in Fig. 7(c). The predicted stress–strain curves of test samples are shown in Fig. 7(c). From this figure, we can expect that Neoprene_2 has the best shock-absorption performance among these samples because the area of the stress–strain curve enclosed can represent the ability to absorb the shock energy during impact. Therefore, from Fig. 7(c), the rank of the performance of shock absorption is Neoprene_2 > EPDM > PVC > Neoprene_1 > polyethylene.

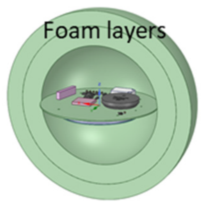
III. Package Design Simulation

A. Comparison of Tennis Ball and Hockey Puck Package

In this study, two configurations—a tennis-ball design and a hockey-puck design—were considered. In Fig. 8, the numerical models are displayed. In this study, the goal is to make the product shorter in height in order to improve its integrity. Meanwhile, the product also has good shock performance in all the drop orientations. Therefore, we chose the tennis-ball design. And, in order to save some volume, then the hockey-puck design was introduced.

There are several electronic components mounted on the PCB, as shown in Fig. 8. Only one huge resistor is kept in place, while other components are removed to reduce calculation time and better understand the dynamic behavior of the PCB. The complete PCB and component are molded using the epoxy molding compound, which can boost the overall product's stiffness. Fig. 8 depicts the distinction between the hockey puck and tennis ball structures. The advantages of a hockey puck construction are that it may save a lot of volumes, as seen in Fig. 9. However, because the spherical design has a thicker foam packing than the hockey puck structure, we can anticipate it will have greater shock performance than the hockey puck structure.

Fig. 10 depicts the deformation of the PCB along the path at the moment when maximum deformation occurs in different



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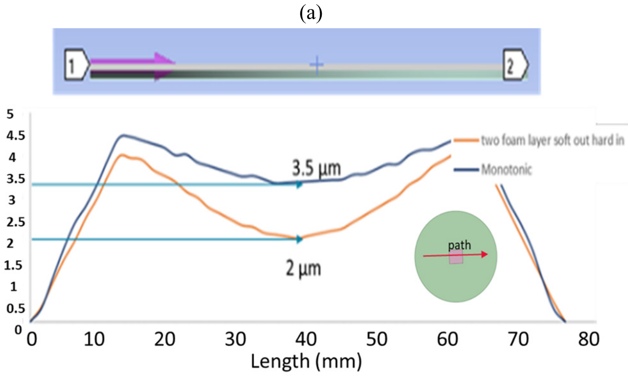

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Fig. 11. Monotonic layer versus double layer. (a) Numerical model of foam layers. (b) Simulation result of monotonic layer versus double layer design.

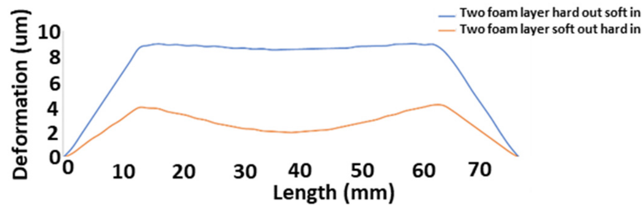
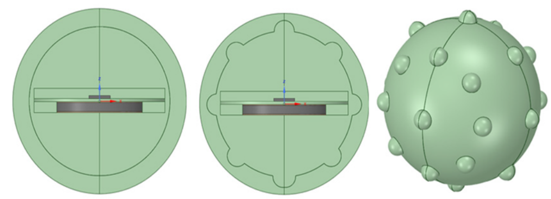


Fig. 12. Different designs of double layer.



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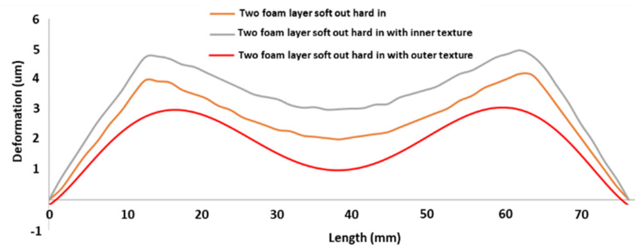


(b)

Fig. 13. Different texture design of a double-layer outer packing. (a) Design of plain, inner dimpled texture, and outer pimple texture. (b) Out-of-plane deformation of PCB across the center path.

drop angles, like bottom drop, side drop, upside-down drop, and corner drop. The results of a comparative simulation of these two structures without texture show that, first, compared to the hockey puck structure, the sphere structure has small deformation at the bottom surface impact case because its inner layer thickness is much greater than that of the hockey puck structure, and it also has a smaller impact area than the hockey puck structure. Second, the hockey puck performs better in corner impact scenarios because it may spin upon corner collision with the ground as opposed to the spherical shape, which only reacts to the air perpendicularly and without rotation. And, based on the simulation results for various drop angles, we see that the bottom surface drop direction is the most severe condition when compared to other drop directions. Thus, we concentrate on the bottom surface drop direction in the following simulations.

B. Single Versus Double Layer Design

Because of the restriction on outer packing thickness, two designs were selected: one uses a single layer and the other a double layer. There are two designs available for the double-layer construction as well. One uses a soft foam exterior to encase a stiff inside. The second uses a hard foam shell to encase a soft interior. Below is a display of the parametric study's findings. When identical simulation settings and materials are used, the deformation of PCB in the single layer of foam case is greater than that of PCB in the double layer case. Fig. 11 shows the results when using a soft exterior over a hard interior. indicating that the double-layer design offers superior shock resistance to the single layer. Fig. 12 shows a comparison of that design with the hard-outside-soft-inside design.

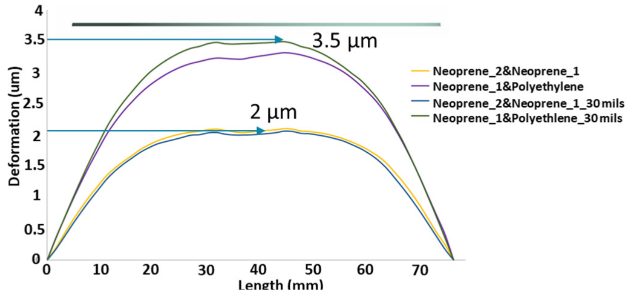
In Fig. 12, the comparison of various double-layer foam packing designs reveals that the soft-outside-hard-inside design significantly reduces the deformation of the PCB when compared with the soft-inside-hard-outside design. As a result, the soft foam exterior and rigid foam interior offer superior shock absorption. As a result, the double-layer foam outer packing design with soft foam outside and rigid foam within was chosen.

C. Texture Design for Packaging

Once the design of the exterior packaging, which is a double layer of soft foam on the outside and firm foam inside, has been chosen, the outside packaging's texture should also be considered. There are three different texture designs: no texture, pimple outside texture, and dimpled texture, as shown in Fig. 13(a). Fig. 13(b) demonstrates that the inner dimpled texture of these three designs has the most out-of-plane deformation of the PCB. It would cost more than the others to manufacture. The out-of-plane deformation of PCB is lowest in the outside pimple texture, though. The pimple exterior texture provides the best shock performance. The double-layer exterior foam packing has been designed with the pimple design.

D. Effect of the Thickness of PCB

After analyzing the effect of the structure of foam packaging, the effect of the thickness of the PCB was also studied. To decrease the deformation of the PCB during drop impact,



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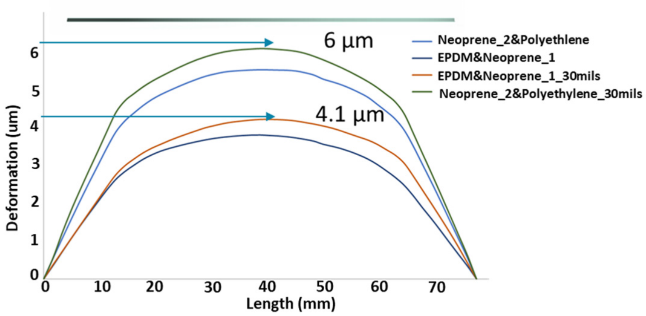


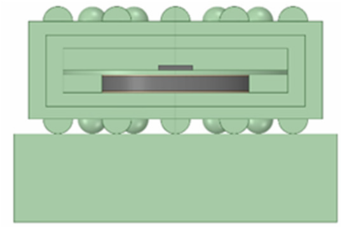
(b)

Fig. 14. Simulation results of different thicknesses of PCB. (a) Tennis-ball design: out-of-plane deformation of PCB across the center path. (b) Hockey puck design: out-of-plane deformation of PCB across the center path.

a good way to improve the stiffness of the PCB is by making PCB thicker. Thus, two thickness options for PCB were provided; one option is 30 mils, and another one is 63 mils. The design of soft-outside-hard-inside and outer pimples using different foam combinations was simulated. The out-of-plane deformation of PCB across the path for tennis-ball and hockey puck designs is shown in Fig. 14. The results show that the thicker PCB can decrease the out-of-plane deformation of the PCB by increasing its stiffness in both tennis-ball and hockey puck design, which follows our expectations. Therefore, the 63-mil thickness PCB would be used in the following design.

IV. Result and Discussion

A double-layer foam packing with an outer pimple texture should be used to protect the internal electronic components. We ran simulations with several foam material combinations to examine their effectiveness in the pimpled soft-outside-hard-inside design. We input the expected stress–strain curves for each foam material into the impact simulation for the sphere and hockey puck drop. The bottom surface drop impact is the most harmful situation, according to the earlier findings. Therefore, only the bottom drop direction was simulated. We used the elastic regions of the developed stress–strain curves of the various materials to consider which material should be used for the soft outside and the firm inside. Fig. 15 displays the outcomes of the simulation for the hockey puck. Fig. 16 displays the outcomes of the simulation for the sphere. According to Fig. 15, the combination that causes the least PCB distortion in a hockey puck design is the EPDM inside layer and Neoprene_1 outside layer. The greatest deformation happens with the Neoprene_2 inner layer and



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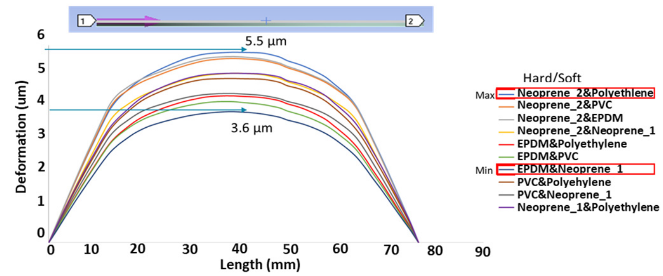
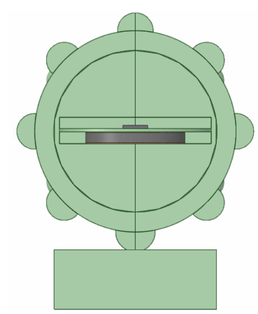


(b)

Fig. 15. Simulation results of hockey puck with predicted stress–strain curve of foam samples. (a) Hockey puck design with pimple outer texture. (b) Out-of-plane deformation of PCB across the center path.



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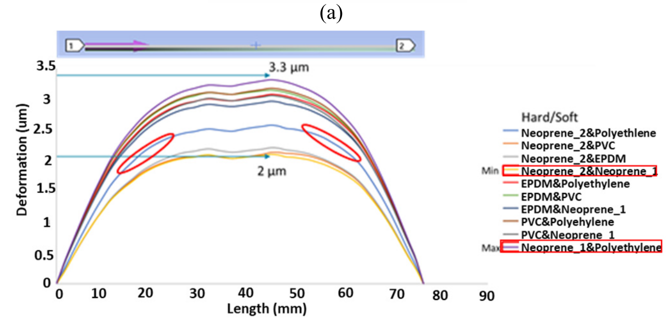

(b)

Fig. 16. Simulation results of tennis ball design with predicted stress–strain curve of foam samples. (a) Tennis ball design with pimple outer texture model. (b) Out-of-plane deformation of PCB across the center path.

polyethylene outside layer. However, in the spherical design, the Neoprene_2 inner layer and Neoprene_1 exterior layer combination yields the best result, which is seen in Fig. 15. And the combination of Neoprene 1 and polyethylene deforms PCBs the most. We can easily see that the PCB has a bending region from the deformation curve of the PCB of the previous hockey puck and sphere simulation results, which is depicted as a red circle in Fig. 16. The important takeaway from this discovery is that it is important to keep electrical components away from the highest deformation zone, which is depicted in

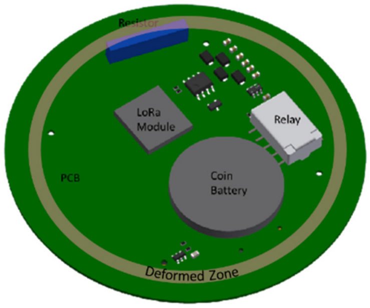

Fig. 17. Dangerous zone for placing component.

Fig. 17 and may result in interconnection failure upon drop impact.

V. Conclusion

A. Packaging Design Simulation

Two different kinds of shapes of foam packaging were included; One is the tennis ball shape. The other is the hockey puck shape. Even though the tennis ball design has lower out-of-plane deformation of PCB during impact, the biggest advantage of hockey puck design is saving huge volume which cannot be ignored. Therefore, based on different applications, either the tennis ball structure or the hockey puck structure can be used.

By comparing different foam materials and designs of foam packaging, the double-layer design (soft-out-hard-in) with outer pimple texture has better shock performance for both the tennis ball design and hockey puck design of foam packaging.

B. Guideline of the Placement of Electronic Components

By performing the system-level drop impact simulation of tennis-ball and hockey puck design, we can understand the dynamic behavior of the PCB during impact and be aware of the most dangerous area on the PCB which shown is in the red circle area in Fig. 16. Therefore, the larger components should avoid being placed across that zone, Fig. 17, which can significantly improve the reliability of the solder joint of larger components.

Acknowledgment

Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of DTRA.

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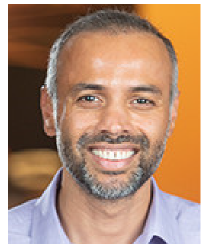

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