Wearable Device Friendly Light and Moisture Dual-Curable Conformal Coating

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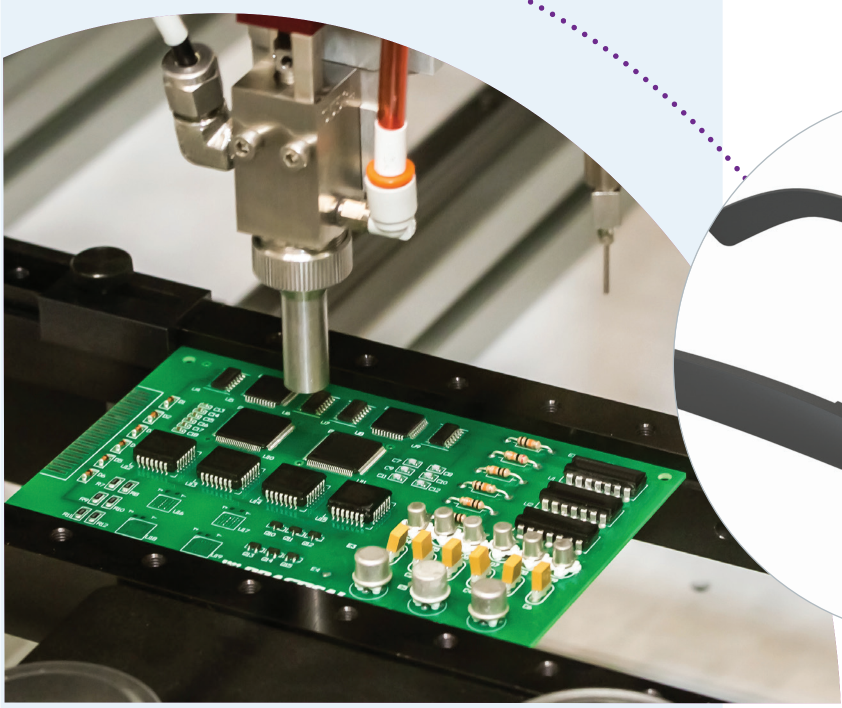
Abstract

Encapsulants and conformal coatings are used to improve and extend the reliability of printed circuit boards against environmental conditions. There is high interest in using light-curable materials due to their process benefits over conventional technologies, including no need for use of solvents, higher throughput, space savings, and lower operating costs. Light and moisture dual-curable encapsulants and coatings were developed to ensure the curing of the material that might flow underneath components on circuit boards. The use of light-curing in wearable consumer electronics has been limited due to skin sensitizer ingredients used in most light-curable formulations. Flexible circuit boards (FCBs) are becoming essential parts of wearable devices that are designed to conform to body parts. A flexible light and moisture dual-curable encapsulant/conformal coating was developed that minimizes skin-sensitizing ingredients and still perform well in reliability tests. In this paper, skin sensitizer ingredients, physical properties, and reliability testing such as heat and humidity (85°C, 85% relative humidity), thermal cycling (-40°C to +85°C), and chemical resistance are discussed. These results are compared against other light-curable encapsulants/conformal coatings.

Introduction

Conformal coatings are thin polymer films applied to printed circuit boards (PCBs) to protect them against environmental factors such as moisture, chemicals, and thermal shock. The use of conformal coatings becomes necessary as the size of the parts decrease and the gap between components or the gap between features of the components decrease. Conformal coatings provide electrical insulation between components or features of the components, provide increased mechanical support, and hence allow design of smaller, more dense PCBs.[1] The typical thickness of the conformal coatings varies between 25 µm to 225 µm. The coating can be applied by a variety of methods, such as dipping, brushing, spraying, and flow coating. Traditional conformal coatings often require thermal curing which is time and energy consuming and can potentially damage sensitive components. Other conformal coating technologies require either use of volatile organic solvents or mixing of two parts.

Light-curable materials emerged in the past several decades as the ideal choice for high-volume manufacturing since they have a very rapid and efficient curing process. Light-curing enables on-demand instant cure and a smaller footprint on the manufacturing floor. Light curable coatings do not require solvent dilution or evaporation, and they can be applied to desired thickness in only one coating layer. There is no need for mixing, as with two-part coatings; no need for explosion-proofing, as with solvent-based materials;



and typically, fewer steps and fewer operators are required for each processing step.[2] In addition, no extra shipping charges are required, as is the case with coatings containing solvents. Light curing is also an ideal technology for heat-sensitive substrates.[3]

Wearable electronic devices, such as smart watches, fitness trackers, wireless headphones and smart glasses have become omnipresent in modern society.[4] As these devices become more sophisticated, expectations on their reliability and durability have increased. Conformal coatings and encapsulants are utilized to extend the lifespan of these devices by protecting the sensitive components from environmental factors and mechanical stress. Light-curing materials have emerged as the preferred choice for manufacturing of wearable devices, as they facilitate the production of smaller devices and enable fast and efficient manufacturing assembly lines.

The free radical curing mechanism is used in most conformal coatings due to its ability to obtain a wide range of physical properties. Typical ingredients of free radical light-curable formulations and their functions are represented in Figure 1. [1] Photo-initiators absorb light and then generate reactive species that initiate polymerization of other ingredients of the formulations. The physical properties of the light-curing materials mostly depend on the oligomers and monomers used in the formulations. Rigid or highly flexible elastic materials can be obtained by choosing the appropriate combination of monomers and oligomers. Monomers are usually introduced as a reactive diluent to adjust viscosity and physical properties.[5]

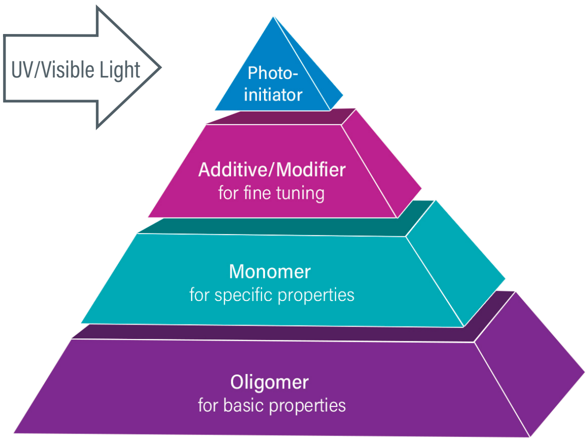


Figure 1. Polymerization Steps in Light Curing

Isobornyl acrylate (IBOA) is one of the most commonly used monomers in light-curable materials due to the unique properties it imparts. Its rigid, bicyclic and nonpolar structure provide enhanced properties like toughness and chemical resistance to the cured material. Additionally, IBOA's low viscosity and excellent compatibility with wide range of oligomers make it a crucial ingredient in various applications such as coatings, adhesives, and inks. While IBOA offers desirable properties for light-curable materials, its use in wearable electronics has become restricted due to its potential to cause skin irritation and sensitization. Wearable device manufacturers have begun avoiding materials containing IBOA, especially after the American Contact Dermatitis Society named it the Allergen of the Year for 2020.[6] Since then, material suppliers started to develop IBOA-free products to be used for wearable devices.

A limitation of light-curing is the curing of shadow areas where light cannot penetrate. Selective dispensing can be used to avoid material flowing into shadow areas, but it would not eliminate the limitation and restrict the use of light-curing in wide range of applications. Light and moisture dual curing materials have been developed to allow curing in shadow areas that are present on PCBs. [7] In light and moisture (LM) dual curable formulations, light-curing enables rapid curing and quick turnaround times while subsequent curing with ambient moisture enables the curing of materials in shadow areas over time.

Light-emitting diode (LED) curing technology offers numerous advantages over traditional mercury-based lamps, including lower operating costs and improved environmental sustainability. As LED technology advances, it's becoming a preferred light-curing method. LEDs offer numerous benefits, including cooler operation for improved thermal management and stable light intensity for consistent process control. LED curing systems provide instant startup, immediate light energy, and a significantly longer lifespan than traditional lamps. [8] To increase the use of LED curing systems, it is essential to develop formulations optimized for LED curing.

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Experimental

Viscosities of the liquid coating formulations were measured according to ASTM D2556. Dynamic mechanical properties were assessed at a frequency of 1 Hz using a dynamic mechanical analyzer, in accordance with ASTM D5418. Cross-cut adhesion testing of the coatings was performed on glass-filled epoxy laminate (FR4) board substrates following ASTM D3359. Mandrel bend tests were conducted per ASTM D522, using a 3 mm mandrel to achieve a 180° bend on polyimide (Kapton®) film and copper sheets. Tensile properties were measured in accordance with ASTM D638. Six tensile samples were used for each testing.

Conformal coatings were applied to boards by precision spraying to achieve a dry film thickness of 75 to 90 µm. Liquid coatings were cured using mercury-based broad-band light (2.50 W/cm² intensity at conveyor belt speeds of 15 to 25 mm/second) or LED light (365 nm wavelength, 1.7 W/cm² intensity for 20 seconds). Curing in a light conveyor is shown in Figure 2. After light curing, secondary moisture-curing formulations were exposed to 40°C and 50% relative humidity (RH) for 3 days to complete the moisture cure. Alternatively, coatings could be cured at 25°C and 50% RH for 7 days. The secondary heat curing formulation was cured in an oven at 120°C for 30 minutes following light curing.

The wetting of uncured liquid conformal coatings on various substrates was tested according to ASTM D7334 using a Goniometer. The contact angle formed between a drop of approximately 6 µL liquid conformal coating on each substrate was reported. Six samples were tested for each coating on the same substrate.

Custom-designed multi-pattern FR4 boards, as shown in Figure 3, were used to evaluate damp heat corrosion resistance. A humidity chamber was set to 85°C and 85% RH for 500 hours to assess the damp heat resistance of the coatings. Upon completion of the reliability tests, samples were maintained at 25°C and 50% RH for a 24-hour stabilization period and then visually inspected for appearance, cracks, delamination, or corrosion on the copper using a digital microscope.

Thermal cycling tests were performed on populated test boards, as shown in Figure 4. The coated boards were exposed to 500 cycles of -40°C and +85°C, with a 30-minute dwell time at each temperature and 10-second transition times between the lowest and highest temperatures. Any cracks in the coatings were inspected under magnification using UV-A light with a 365 nm lamp.

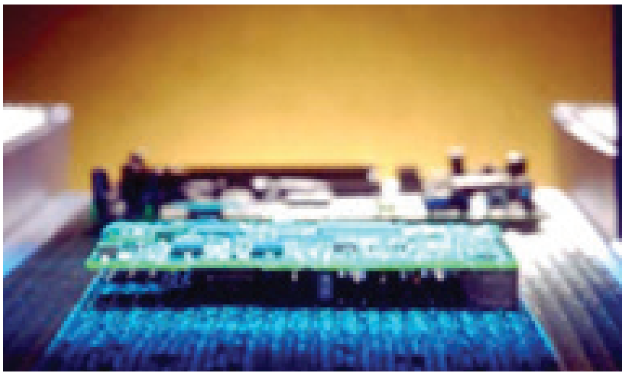


Figure 2. Light curing of coatings in a conveyor

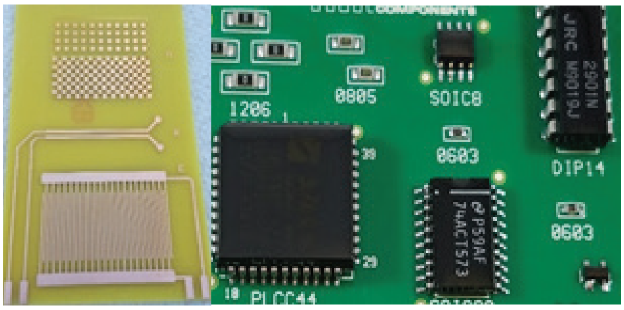


Figure 3. Multi-pattern FR4 test coupon and populated test board

Results and Discussion

As wearable devices get smaller and reliability demands grow, conformal coatings have become essential for their PCBs. Light and moisture dual curable (LM) conformal coatings represent an attractive option for improving the reliability, throughput, and size of electronic devices. The secondary moisture curing mechanism facilitates the curing of the material in shadowed areas, eliminating the need for specialized conditioning prior to subsequent manufacturing processes.

Wearable electronics increasingly rely on flexible printed circuit boards to accommodate the body's contours and minimize device size. To maintain their functionality and longevity, it's crucial to apply coatings and encapsulants that are also flexible. These materials must be able to withstand bending and flexing without cracking or delaminating. However, traditional flexible, light-cured materials often compromise protection against environmental factors like moisture due to their lower crosslinking density. Designing a flexible light and moisture curable conformal coating that could meet the reliability requirements of wearable devices was the main purpose of this work. In addition, LED-curability was also prioritized for improved process efficiency and sustainability.

Description of the conformal coatings tested are given in Table 1. The coating designated as LEDM is the novel flexible LED light and moisture coating developed for wearable applications. LH was used as a flexible conformal coating benchmark whereas LM was used as a rigid high moisture resistance conformal coating benchmark. LEDM does not contain any IBOA in its formulation whereas both LH and LM coatings contain IBOA. Both LH and LM needed to be cured with mercury based broad band light sources whereas LEDM was cured with an LED light.

Average of the cured tensile properties of the coatings with their standard deviation (stdev) are given in Table 2. LEDM had the highest tensile strength and elongation values. LH had slightly lower tensile strength and elongation than the LEDM. LM had significantly lower elongation and significantly higher Young's modulus compared to the LEDM and LH. Therefore, from here on in this paper, LEDM and LH will be referred to as flexible coatings whereas LM will be referred to as a rigid coating.

Table 1. Description of the Conformal Coatings Tested

	Chemical Classification	Light Source for Curing	Curing Mechanism	Viscosity (cP)
LEDM	Urethane Acrylate	LED	Light + Moisture	1000
LH	Urethane Acrylate	Broadband	Light + Heat	2300
LM	Urethane Acrylate	Broadband	Light + Moisture	750

Table 2. Tensile Properties

	LEDM	LH	LM
Tensile Strength (MPa) [stdev]	17 [2.5]	14 [1.9]	14 [0.8]
Elongation-at-Break (%) [stdev]	143 [13]	133 [9.5]	21[3.9]
Young's Modulus (MPa) [stdev]	274 [15]	146 [22]	684 [67]

The tensile properties of the coatings before and after secondary curing are presented in Table 3. Traditional light and moisture cured conformal coatings, such as LM, rely heavily on moisture curing to achieve their final mechanical properties. Consequently, LM exhibits significantly lower tensile strength and Young's modulus after light curing alone. In high-throughput wearable electronics manufacturing, coatings are expected to demonstrate high strength and resistance to deformation immediately after light curing to prevent the occurrence of defects. The novel LEDM conformal coating was designed to provide significantly higher initial strength and stiffness, enabling it to withstand external stresses even without moisture curing.

Good wetting of substrates is essential for conformal coatings to achieve optimal adhesion, prevent defects, and enhance reliability. To assess wetting properties, contact angle measurements were conducted on FR4, solder masked FR4, and Kapton® substrates. The average contact angle values, presented in Table 4, indicate that LM exhibited the lowest contact angle on all three substrates, followed closely by LEDM. LH had higher contact angle values.

Predicting the reliability of conformal coatings is crucial for the development of high-performance materials. Rigid coatings can induce stress on components, solder joints, or even crack during thermal cycling due to expansion and contraction. Dynamic mechanical analysis (DMA) is a technique used to assess how material properties change with temperature. By applying oscillating force to a coating film, DMA measures its deformation response. Storage modulus, which quantifies the material's resistance to deformation, is a key parameter. [2] Higher storage modulus materials are expected to better withstand elevated temperatures, while lower modulus materials may be less prone to cracking during temperature fluctuations, particularly at sub-zero temperatures. The glass transition temperature (T_g) marks the transition from a glassy to a rubbery state, significantly influencing a material's thermal expansion and contraction behavior. Materials can be engineered to have higher T_g to better withstand higher operating temperatures, thereby minimizing thermal expansion and contraction. Alternatively, materials can be designed to be more flexible, as in the case of LEDM, to reduce the stress they may generate on components.

Table 3. Tensile Properties Before and After Secondary Curing

		Tensile Strength (MPa) [stdev]	Elongation-at-Break (%) [stdev]	Young's Modulus (MPa) [stdev]
LEDM	Before moisture cure	13 [1.5]	153 [19]	140 [8.7]
	After moisture cure	17 [2.5]	143 [13]	274 [15]
LH	Before heat cure	11 [0.5]	143 [4.8]	84 [8.7]
	After heat cure	14 [1.9]	133 [9.5]	146 [22]
LM	Before moisture cure	1.5 [0.3]	52 [7.1]	13 [2.7]
	After moisture cure	14 [0.8]	21 [3.9]	684 [67]

Table 4. Average Contact Angle Values

	LEDM	LH	LM
Average Contact Angle on FR4 (o) [stdev]	41 [3.5]	52 [5.8]	40 [1.3]
Average Contact Angle on Solder Mask (o) [stdev]	48 [4.0]	58 [3.4]	43 [3.9]
Average Contact Angle on Kapton® (o) [stdev]	39 [2.7]	45 [4.2]	34 [0.9]

The dynamic mechanical properties of the cured films are summarized in Table 5. All coatings exhibited T_g below the standard damp heat reliability testing temperature of 85°C and within the thermal cycling reliability testing range of -40°C to 85°C. LEDM displayed the lowest storage modulus at -40°C, which may enhance its performance at low temperatures. LM exhibited a higher storage modulus at 85°C, which is expected to improve its performance at elevated temperatures.

Chemical resistance provided by the conformal coatings were tested by soaking coated boards for 72 hours into one of the respective chemicals. None of the coatings showed any delamination after the soaking process. To test adhesion retention, crosshatch adhesion test was performed 24 hours after the boards were removed from the chemicals. Table 6 lists the crosshatch adhesion results before and after exposure to chemicals. In a crosshatch adhesion test, a 5B rating signifies excellent adhesion with no coating removal, while a 3B rating indicates moderate adhesion with small flakes of the coating removed. LEDM did not show any loss of adhesion with six of the eight chemicals. Slight adhesion loss was observed with sunscreen and artificial sebum. As can be expected from a rigid conformal coating, LM performed the best with only slight adhesion drop with water and isopropanol mixture.

Table 5. Dynamic Mechanical Properties

	LEDM	LH	LM
Glass Transition Temperature (°C)	57	47	50
Storage Modulus at -40°C (MPa)	1239	1515	1514
Storage Modulus at 25°C (MPa)	442	212	725
Storage Modulus at 85°C (MPa)	12	17	29

Table 6. Crosshatch Adhesion After Chemical Soak

	LEDM	LH	LM
Initial	5B	5B	5B
50:50 water / isopropanol mixture	5B	5B	4B
30 SBF Sunscreen	4B	3B	5B
Body lotion	5B	5B	5B
Artificial Perspiration	5B	5B	5B
Artificial Sebum	3B	5B	5B
Bug Spray	4B	5B	5B
Perfume	5B	5B	5B
Coffee	5B	5B	5B

Table 7 presents images of the multipurpose patterned boards after undergoing 500 hours of 85°C/85% RH damp heat reliability testing. None of the coatings exhibited delamination or cracking. However, the LH coating demonstrated the poorest performance, as the copper patterns beneath the coating darkened and exhibited localized corrosion, likely due to oxidation. In contrast, LEDM, a flexible conformal coating similar to LH, functioned as an excellent protective coating, preventing any visual indication of copper corrosion.

Thermal cycling (-45°C to 85°C, 30-minute dwell time, 500 cycles) were performed on solder masked test boards that were populated with various chips. Table 8 shows magnified images under UV-A light of a selected part on the boards after the thermal cycling testing. LM had performed the worst in terms of crack formation on the coating after the test. Both LEDM and LH performed well with no sign of cracking.

Table 7. Damp Heat Reliability Test

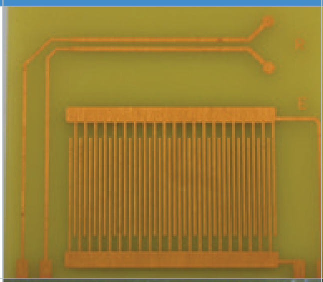
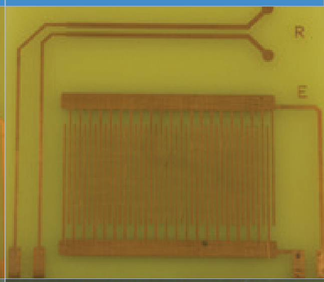
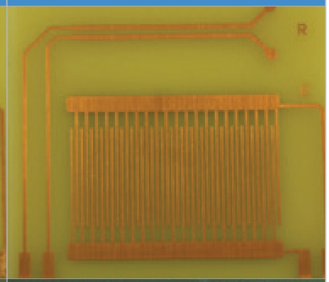
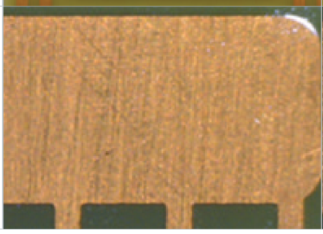
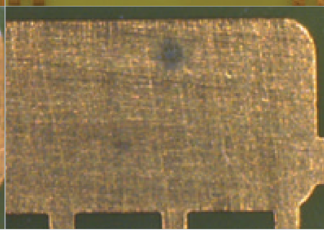
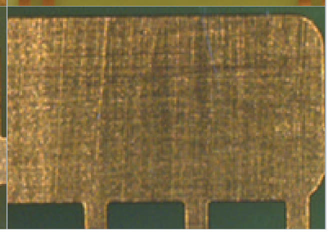
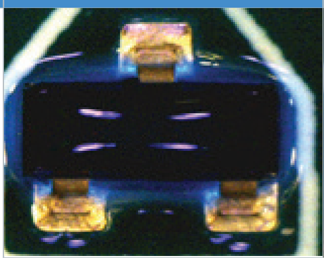
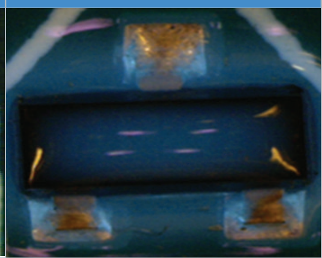
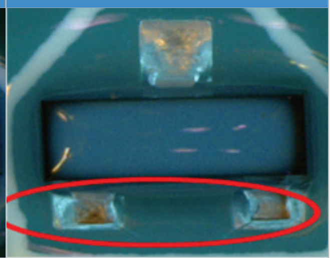
	LEDM	LH	LM
Coated Boards after Damp Heat Reliability Test			
Magnified Copper Pattern after Damp Heat Reliability Test			

Table 8. Temperature Cycling Reliability Test

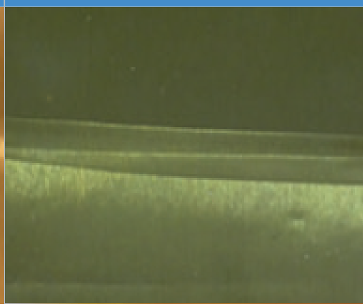
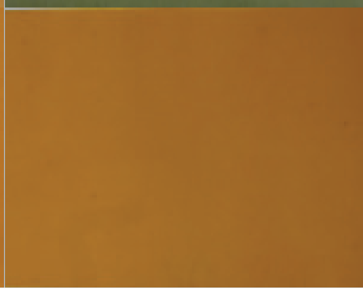
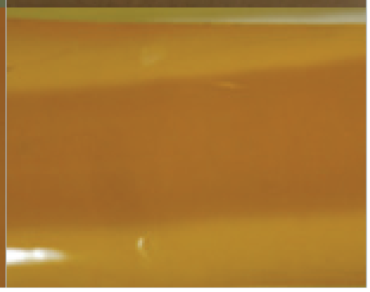
	LEDM	LH	LM
After Thermal Cycling	 	 	 

To ensure the long-term reliability of FCBs, conformal coatings must maintain their flexibility. Copper sheets and Kapton® films coated with the conformal coatings were subjected to 500 hours of damp heat resistance testing followed by Mandrel bend testing to assess retention of flexibility. Table 9 demonstrates images of the coated substrates after Mandrel bend testing. LEDM demonstrated the best performance on copper, exhibiting no signs of cracking, delamination, or corrosion. LH exhibited cracking, indicating a loss of flexibility. Furthermore, the copper beneath the coating exhibited a greenish discoloration, indicative of oxidation. LM did not show cracking but could not prevent copper discoloration. No delamination or cracking was observed on the Kapton® films. However, LM induced warpage in the Kapton® film, likely due to the stress exerted by the coating.

Conclusion

A novel flexible, light and moisture dual-curable conformal coating has been developed to meet the reliability requirements of wearable electronics. This coating offers several advantages over traditional light and moisture dual-curable coatings, by exhibiting superior initial mechanical properties, enhanced flexibility, and improved resistance to environmental factors. Its ability to retain flexibility and withstand damp heat conditions on both Kapton® and copper substrates makes it well-suited for wearable devices incorporating flexible circuit boards. By addressing the limitations of existing technologies and prioritizing skin safety, this coating has the potential to significantly advance the reliability and durability of wearable devices.

Table 9. Mandrel Bend Test after Damp Heat Reliability Test

Substrate	LEDM	LH	LM
Copper Sheet			
Kapton® Film			

References

[1] Dymax Company Literature, "Increase PCB Performance and Productivity with UV Light-Curable Conformal Coatings and Maskants". https://cdn.bfldr.com/OIYY7HMJ/at/cg2vps8bsxmwnwrc86fm6k24/WP011_US_EN_-_Conformal_Coatings_and_Masking_White_Paper.pdf

[2] Wicks Z.W., Jones F.N. Pappas S.P. (1999). Organic Coatings Science and Technology: Second Edition. New York John: Wiley and Sons.

[3] Dymax Company Literature, "An Introduction to UV Light-Curing Technology". https://cdn.bfldr.com/OIYY7HMJ/at/4sb5bqg4kpgjbkp7t875mxk/An_Introduction_to_Light-Curing_Technology_eBook_US_EN.pdf

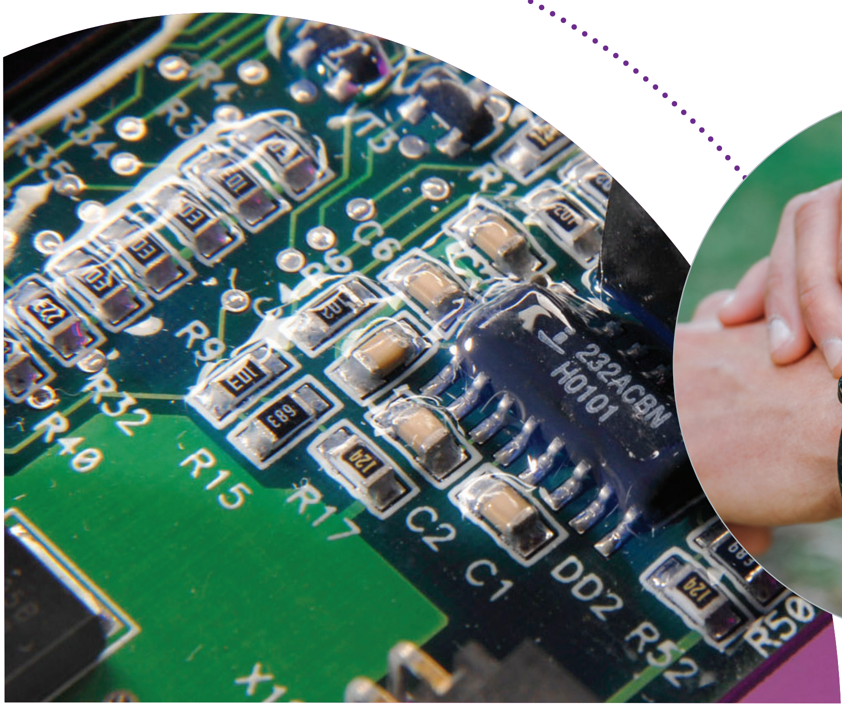
[4] Nelson E.C., Verhagen T., Vollenbroek-Hutten M., Noordzij M.L. (2019). Is Wearable Technology Becoming Part of Us? Developing and Validating a Measurement Scale for Wearable Technology Embodiment. JMIR Mhealth Uhealth, Pages 1-12.

[5] Swaraj P. (1996). Surface Coatings: Science and Technology: Second Edition. New York: John Wiley and Sons

[6] Cichon M., Trzeciak M., Sokolowska-Wojdylo M., Nowicki R.J. (2023). Contact Dermatitis to Diabetes Medical Devices. International Journal of Molecular Sciences, Pages 1-13.

[7] Dymax Company Literature, "High Performance Light and Moisture Dual Curable Automotive Conformal Coating". https://cdn.bfldr.com/OIYY7HMJ/at/chpf6pckvjktjfjb6hmqwb2q/WP012_US_EN_-_High_Performance_Light_and_Moisture_Dual_Curable_Automotive_Conformal_Coating.pdf

[8] Dymax Company Literature, "Optimizing an LED-Curing System", https://cdn.bfldr.com/OIYY7HMJ/at/f7nq9qttqgr7xrvtb9wq9/WP002_US_EN_-_Optimizing_an_LED_Curing_System.pdf



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