TECHNICAL ARTICLE

Use of Color-changing Pigment to Detect Wire and Cable Hazards

This technology represents an opportunity for forward-looking wire and cable manufacturers to provide and market new cables that meet the increasing demand for safer products.

By Walt Ogrodnik

This paper presents the latest technology of color-changing thermochromic substances for wire and cable professionals, focusing on thermochromic applications to the insulation/jacketing of electrical conductors (including plugs) to detect thermal hazards. Thermochromics are poised to transcend their prior novelty and food temperature applications by providing an efficacious, high-value, low-cost substance for innovative color-changing wire and cable safety uses.

The paper begins with a brief scientific description of various classifications of "Chromism," including the two most common types of chemical colorants used in thermochromic color applications today. One colorant, in particular, is the focus of this paper, i.e. color-changing Leuco Dyes (LD). The paper also addresses some of the principles and more common conditions leading to hazardous conductor over-heating; some statistics about damage caused by undetected wire and cable faults; best practices for the extrusion/injection process; and non-extruded/injected LD applications. Finally, for an industry constantly competing with price-sensitive generic wire and cable commodities, there is a detailed model of the typical financial costs and expected returns, along with a market survey summary on consumer pricing and preference.

The science of chromism

Chromism is a process that induces a change (typically reversible, yet, it can be irreversible) in the colors of certain compounds. In most situations the change is based on external stimuli which, in effect, transfers energy and alters the density of the electron state of the molecules. It is the absorption of this energy and subsequent reflection of light in different wavelengths that causes a color change.

There are many artificially synthesized, as well as natural, compounds that exhibit chromism. Specific classes of chromism are generally divided by the external stimuli required to induce or create the change. The most common chromism classes today are: Thermochromism, which is induced by temperature (the focus of this paper); Photochromism, is induced by light irradiation; Electrochromism, which is induced by the gain or loss of electrons; Solvatochromism, which is induced by the polarity of solvents; Ionochromism, which is induced by an exchange of ions; Piezochromism, which is induced by mechanical pressure; Tribochromism, which is induced by mechanical friction; and Hydrochromism, which is induced by a change in moisture.

Examples of chromism include liquid crystal and LED display screens, films, Transition® eyeglasses, Hot Wheels® toy cars, thermal print paper, carbonless paper, aquarium thermometers, Energizer® and Duracell® battery testers, etc.

Principles of Thermochromism

Materials that undergo temperature-induced color changes are said to be thermochromic. See Fig. 1. The two major types of thermochromic material most used for commercial purposes today are Liquid Crystals (LC) and Leuco Dyes (LD).

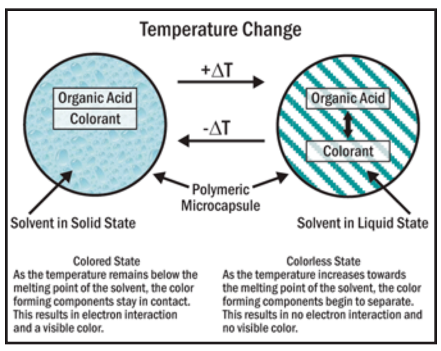

Fig. 1. Principle of Thermochromism.

Liquid Crystals (LC). These crystals (of the thermochromic cholesteric type) possess both liquid (flow) and optically solid (anisotropic) properties. They are very sensitive to temperature in that, thermal expansion (within a narrow range) results in a change in spacing, pitch and layering, hence, discernable reflection of changing wavelengths of light from their structures. LC can be modified in their composition to respond to very specific temperature ranges although color density and color choice is very limited.

Because of the inherent sensitivity of LCs, they are used in many applications where very precise readings of temperature are required, such as children's forehead thermometers, vaccine vials and even mood ring jewelry. The most common method of applying LCs is by inking them on to a substrate. While LCs are very temperature sensitive, they are neither inexpensive nor easy to process or apply. Hence, LCs are typically used in limited applications of higher value and in smaller quantities.

Leuco Dyes (LD). These dyes are the other and most common of all thermochromic material in commercial use today. Three major components makeup most LDs including; the leuco dye, a weak acid and a solvent. LDs work because of a temperature induced change in the solid form of the material. As the material gently melts, the pH inside the LDs shell lowers and the LD becomes protonated, consequently shifting its color absorption dramatically.

LDs are unique in that they are normally colored in their cool state and, when temperature activated, they transform to a colorless (actually translucent) state. This property allows for many color combinations (cold and hot) when the "clearing temperature" (i.e., the temperature when the material becomes colorless) of the LD is reached. Since the opaque/cold LD becomes colorless when heated, the LD allows the underlying or "hot" color to be visible. LDs are able to be creatively combined with other LDs of different clearing temperatures (and color opacities) to create sequential and near animated changes at increasing clearing temperatures and with different colors. The current range of clearing temperatures can be as low as -10°C to as much as 70°C+ and can be fabricated in almost any color.

Unlike the LCs, the LDs have very robust color possibilities. They are relatively inexpensive and substantially easier to process and apply. However, LDs are not nearly as accurate at changing color at a precise temperature when compared to LCs. Typically, color will begin to change over a 2-5°C range although certain LDs have been processed to have more or less of a range. Further, LDs exhibit a unique and desirable property for the wire and cable industry called "Hysteresis." This property, which is defined as a lag or delay in response to the change of stimuli (in this case it is the returning temperature decrease), causes the return color change to maintain its colorless state until it cools 2-5°C below the temperature at which it originally "cleared" during the warming process. The desired range of hysteresis is another variable that can be customized by the encapsulation processor. See Fig. 2.

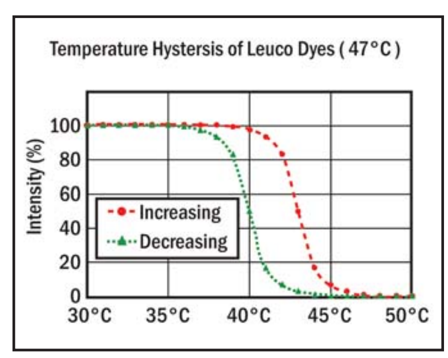

Fig. 2. Hysteresis of Leuco Dyes.

Most LDs used today are reversible. However, LDs can be fabricated to change colors only once when a certain pre-selected temperature is reached. This one-time change involves using stronger acids within the microencapsulation shell that effectively arrest any further electron exchange.

While polymerized LDs are used for injection and extruding, they can also be used on as a topical color-changing ink on wire and cable that can be contact printed in wheel-printing, embossing, and hot foil applications; used for pattern printing (e.g., banding, hash marks, spiral or longitudinal striping); or for verbiage or numerals.

LDs can be used effectively on adhesive wrap-around labels for retro-fitting existing conductors. This type of LD application (which can be made UV/weather tolerant) is often irreversible or historical. Irreversible color-change labels are often applied to wire and cable since the label can have multiple temperature settings (including high temperature settings exceeding 150°C+) and can be replaced if required. Hidden wiring and/or "warranty voiding" is also a practical application for such labels.

Microencapsulation of Leuco Dyes

Leuco Dyes (and liquid crystals) must be microencapsulated before use. See Fig. 3. Microencapsulation of the organic dyes adds stability, color, temperature control and protection of the coloring agents from the environment. In this process, the small particles of color-changing pigment (called the "core material") are carefully coated with a shell. An interfacial polymerization process is used to form the shell around the dye and solvent. The microencapsulation process and material of the shell and the resultant quality and thickness are primarily responsible for dictating the temperature responses, including the previously explained hysteresis phenomenon. Some microencapsulators claim to have nearly eliminated hysteresis in their LD material.

The process of microencapsulation is complex and critical to the quality of the thermochromic material and end application. Better microencapsulating labs incorporate many important factors and additives in their end product such as, particle size, shell thickness, thermal stability, impermeability, shear strength, and compatibility with the surrounding material to be used. UV additives can also be processed into one of the shell layers. It is therefore critical to identify a LD supplier that will listen and compound to the functional needs of wire and cable manufacturing.

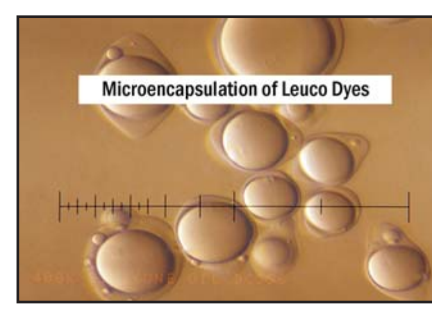

Fig. 3. Microencapsulation photo.

A world of color and patterns

LDs come in virtually every color in both cold and hot form. LDs lose their color when they reach their "clearing temperature." When properly mixed with a clear polymer, the plastic should be opaque when cold and nearly clear when hot. See Fig. 4.

LDs can be combined with other pigments to affect both the cold color and the resulting hot color. For example a "blue to clear" LD combined with a generic 1-3% yellow colorant will take on a green cold look (blue + yellow = green). When the LD heats up and "clears," the visible hot color becomes the yellow underlying color. In all combinations, the cold color needs to be a darker color than the lighter hot color.

Fig. 4. Color-changing cable prototypes.

Even more interesting and complex than the above is the ability of LDs to be combined with two or more LDs with different clearing temperatures in the same plastic. One example would be to start with the above [green (cold)] to have a color change at 105°F (to warm yellow) while a second color change (using the same or different coloration) could take place at 115°F (say

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to hot clear). (If no hot color is used, then by default the hot color becomes the color of the polymer used.) In effect, one can produce a double (or triple) animated sequence of color change over predetermined temperature ranges.

Finally, it should be noted that while color to color (-less) change is the heart of LDs, the creative use of patterns that appear or disappear can become a powerful alerting mechanism in itself or for those who are colorblind or visually challenged. One example is the use of striping. The striping effect can also be applied as an "inked" spiral stripe, albeit the stripe would be more prone to abrasive and strong solvent effects. As in the examples above, consider a spiral blended (not visibly noticeable) onto the surface of the wire and cable, as the underlying color disappears the ink spiral now (as a "candy-cane" pattern) is contrastingly very noticeable.

Principles of wire and cable overheating

The carrying capacity of a conductor is commonly defined as the amperage it may safely handle. See Table 1. Theoretically, the amount of current that can pass through a single bare copper conductor is limited by the melting point of the bare copper (i.e., 1980°F). However, the polyolefin or PVC insulation/jacketing on most wires and cables will begin to melt at about one-tenth of that temperature.

Electric current passing through a conductor always incurs some resistance resulting in heat. Under normal conditions where the conductor is sufficiently sized and properly wired, the heat produced by resistance is not problematic. However, when multiple wires are bundched in a confined conduit, for example, the cumulative heat can lead to hazardous over-heating conditions.

The case for a color-change alert

While advances in circuit interrupters (including GFCI, AFCI, wire and cartridge-type fuses, etc.) working on combinations of heat and electrical current have had a mitigating effect on faulty electric circuits, such devices have their limitations and drawbacks. The biggest problem is the expense to purchase and install such devices. Further, there is the issue of whether the device is properly sized and working for the potentially changing conditions. Many such devices have failed over time. Also most devices are either "On or Off" basis and lack a way to show an escalating condition.

In large commercial/industrial wiring systems, where wire and cable are visible, infrared cameras are now being used to monitor overheating conductors. Maintenance, Repair and Operation (MRO) personnel understand the associated costs with circuit shut-downs and that many such malfunctions are due to slowly aggravated chronic conditions. Households with numerous extensions cords also understand the safety and fire prevention benefits of an alerting color-changing cord. Several influential regulatory agencies have expressed interest in further development of the color-changing wire and cable.

Another consideration and potential advantage/disadvantage in the use of LD on wire and cable (since it can inadvertently give a false electrical alert), is that all LDs will change colors regardless of the source of heat. This means that wire and cable will change colors when it is exposed to the convection heat of a hot space heater or other hot appliance, or even if it has been placed near or on a very hot surface, such as an automotive engine.

By having a pre-alerting system, a user can see when conductor conditions progressively deteriorate. With such visual alerts, the user may be able to circumvent costly circuit shut-downs, prevent more extensive damage to load devices, lower maintenance and repair cost, and perhaps most importantly, mitigate the extensive risk to human lives.

LD suppliers

Few U.S. based companies supply microencapsulated LD material for plastics (see references). The original processing was developed and patented by the Matsui Shikiso Chemical, Co., Ltd., of Japan in the late 1980s. When the original patent expired in early 2000, several companies began R&D to microencapsulate LDs using proprietary processing methods and materials.

Most but not all U.S. suppliers obtain their encapsulated LD material already prepared from sources in Japan, Taiwan, England, and France.

Best production practices and lessons

Based on numerous wire and cable prototyping experiences of the author's company (see Fig. 4), the following production methods have been established. It is noted that variations among LD material/suppliers, polymer types, processing methods, equipment and even colors will have an effect on individual end results.

Some whiteners such as TiO_2 will visually block the LD color intensity and should be avoided. $CaCO_3$ and other fillers may also affect the final LD color intensity, but not the the dominating affect of whiteners.

LD material is slightly 'hygroscopic' and is best kept in dry storage and pre-dried before actual use.

LD material can withstand processing temperatures of approximately 450°F+. Processors can exceed this temperature slightly and momentarily if done when shear force or stress on the LD is light. Excessive heat, shear, or mixing should be avoided with certain solvents as they may harm the LD encapsulation.

Most LD provided in concentrated masterbatch form will only contain from 10-20% actual pigment. Powdered concentrate LD is also available and contains nearly 100% pigment. Certain LD suppliers provide their LD masterbatch in end-use polymer matches (i.e., PE, PVC, PP, etc.), while others use EVA as a 'Universal' base polymer resin.

Dilutions of the concentrated masterbatch are typically around 1:10 but depend on the thickness (~30-40 mil) of the insulation/ jacket and the diluting polymer's ingredients. It has been shown that the clearer the diluting material the better the opacity of the LD and the less LD material is needed. Thicker extrusions require less material than thinner extrusions (i.e., most plugs would be very opaque using a 1:20 dilution or less if using a clear polymer base). Using concentrated LD powder translates to approximately the same total percent of pigment use as other colorants, i.e., approximately 1-3% loadings.

All LDs are sensitive to UV radiation. However, irreversible LD can be made UV tolerant. Certain colors fade more easily with UV. While certain UV inhibitors, stabilizers and other additives can be added, more R&D is required to produce an acceptable long term outdoor grade. One commercial LD encapsulator incorporated UV protection in its outdoor LD products which are currently being used on bridge surfaces to alert drivers to freezing temperatures. Until more UV protection is perfected, wire and cable produced with LDs should be used away from strong UV light.

Summary and future

The first-generation of color-changing wire and cable and plugs has already been prototyped and initially tested. Preliminary analysis indicates the samples fall within regulatory compliance tests for the wire and cable industry. All compounded LD material being used is believed to meet RoHS standards, as well. Currently, several "preferred compounders" are devoting additional R&D effort to "best formulating" the plastics to ensure the masterbatch pelletized concentrate and/or "ready to use" forms are commercially feasible for specific targeted markets. These same compounders may soon be approaching wire and cable manufacturers to ensure such "best formulas" and specific cold/hot colors and "clearing temperatures" have been standardized for orderly market introduction and acceptance.

Despite the remaining fine tuning of LD compounding before eventual commercialization and licensing to the wire and cable market, the biggest hurdle to wide-spread introduction is expected to be the industry itself. The wire and cable industry is, in general, a mature commodity producer under intense pressure to reduce costs and to compete with off-shore producers. LDs will add incrementally to the unit cost of production and like any new innovation there may still be a perceived risk/cost which only a few selective wire and cable manufacturers (more visionary and early adopters) will be able to justify. Optimistically, LD costs are minimal compared to the potential profit margin and market share gains for both the wire and cable manufacturer and the compounder. Perhaps most importantly and more difficult to quantify, the color-changing wire and cable user should experience a reduction in property damage and maintenance costs, with a priceless improvement in the safety to human life.

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Other: Consumer Product Safety Commission, www.cpsc.gov, and National Fire Protection Association, www.nfpa.org. | WB

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Walt Ogrodnik is the CEO of HazardGuard Safety Wire, Inc., Pittsburgh, Pennsylvania, USA. He worked for 17 years as the Sr. VP/COO of a professional systems integration company in Pittsburgh. His prior work experience included eight years in international development with the U.S. Foreign Service. He holds a master's degree in economics from Texas A&M University and an undergraduate degree from Pennsylvania State University. This paper, which was presented at WAI's 77th Annual Convention, Cleveland, Ohio, USA, June 2007, won the Urbain J.H. Malo Memorial Medal Award for best electrical paper.

Electrical Carrying Capacity of Single Copper Conductors (Using Various AWG and Insulation Types in 30C Ambient Temp.)			
Conductor Size	Polyethylene Neoprene Polyurethane Polyvinychloride (Semi-Rigid) At 80°C	Polypropylene Polyethylene (High Density) At 90°C	Polyvinychloride PVC (Irradiated) Nylon At 105°C
30 AWG	2	3	3
28 AWG	3	4	4
26 AWG	4	5	5
24 AWG	6	7	7
22 AWG	8	9	10
20 AWG	10	12	13
18 AWG	15	17	18
16 AWG	19	22	24
14 AWG	27	30	33
12 AWG	36	40	45
10 AWG	47	55	58
8 AWG	65	70	75
6 AWG	95	100	105
4 AWG	95	135	145
2 AWG	125	180	200

Table 1. Carrying capacity of copper wire, in amps.