Electrostatic Issues in Roll-to-Roll Manufacturing Operations

Kelly Robinson and William Durkin

***Abstract*—We present a survey of electrostatic issues in roll-to-roll (RtR) manufacturing operations, use of electrostatic fieldmeters to diagnose static problems, and effective methods to dissipate charge. Electrostatic issues are usually caused by tribocharging between two chemically dissimilar materials but rarely arise from static charge separated during a single contact. Rather, charge accumulates from multiple contacts until there is enough to cause problems. Eliminating static charge at the source is the most cost-effective solution to static problems. Construction materials for manufacturing equipment, equipment design, and product formulation should be selected to minimize static-charge separation. The electrical conductivity of rubber- or polymer-covered rollers should be sufficiently high so that the charge dissipates within one roller revolution. Electrically conductive antistatic coatings may be included in film products to reduce static problems. Because manufacturing operations can be quite complex, having a model or framework in which to organize information is most valuable. An existing model for charge separation and accumulation is extended to include common issues in RtR manufacturing operations. From this model, it is apparent that static monitors are valuable tools to track the charge present in a manufacturing process. High static levels resulting from assignable causes can be identified by control charting the readings from permanently mounted electrostatic fieldmeters. Areas of high electrostatic field may be identified by using appropriate portable electrostatic-fieldmeter measurements to identify where to install charge-dissipation technology to make it most effective.**

***Index Terms*—Charge, conductivity, dissipation, electrostatic, fieldmeter, monitoring, resistivity, static, tribocharging.**

I. Introduction

In ROLL-TO-ROLL (RtR) manufacturing operations, electrostatic issues are caused by electrostatic charge that separates when two chemically dissimilar surfaces touch and separate, as shown in Fig. 1. Rarely does sufficient charge separate in a single contact to cause problems. Rather, charge accumulates from multiple contacts until there is enough to cause problems. In this paper, Glor's model [1] for charge separation and accumulation is extended to include common issues in RtR manufacturing operations. From this extended model, it is apparent that static monitors can measure the charge present in a manufacturing process and that charge-dissipation technology will be most effective at locations where charge accumulates.

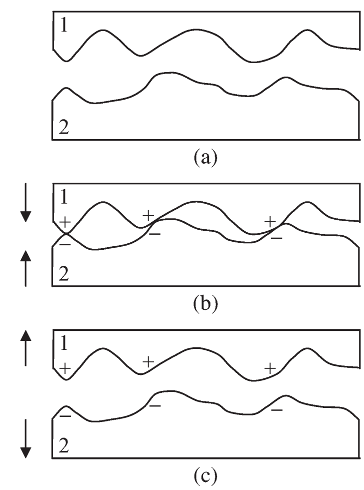

Fig. 1. Electrostatic charge is separated whenever two chemically dissimilar surfaces touch and separate. Here, material 1 is more positive on the triboelectric series than material 2. Prior to contact in (a), both surfaces are neutral. Upon contact in (b), charge separation occurs at the points of contact. At a microscopic scale, only a small amount of surface area actually touches. Upon separation in (c), the surfaces are charged.

A. Advantages of RtR Manufacturing

"RtR" manufacturing is a production process where the end product is built on a thin flexible web, such as in printed electronics or RFID tags, or the end product is a thin flexible web, such as packaging materials. In RtR manufacturing, using a long continuous web to transport the end product through the manufacturing process provides important advantages including high processing speeds, high production volume, precise control during the production process, and fast changeover between production runs [2]. While RtR manufacturing technology has been used in the paper production and printing industries since the 1800s, many new applications are emerging, such as printed electronics [3], the assembly of electronic displays [4], and the production of inexpensive solar cells [5]. These new applications are enabled by high-speed precise technologies such as gravure printing of electrically active organic materials, laser exposure, laser etching, precise molding, and ultraviolet curing.

B. Electrostatic Issues

Electrostatic issues have been recognized in RtR manufacturing since at least the 1950s when electrostatic charge

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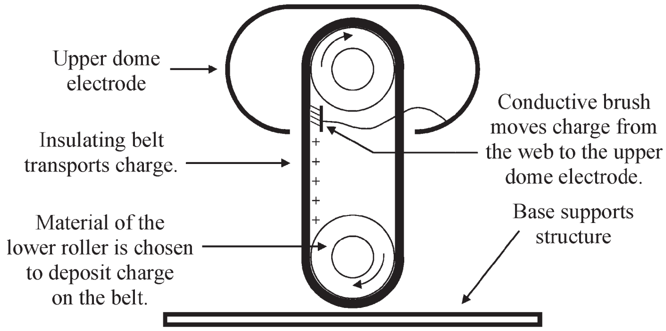

Fig. 2. Illustrated is one version of a Van de Graaff generator where electrostatic charge deposited on a moving belt is the basis of operation. For efficient operation, a large amount of charge must be deposited on the belt by the lower roller, the moving web must be highly insulated, and web charge must be removed efficiently at the upper roller.

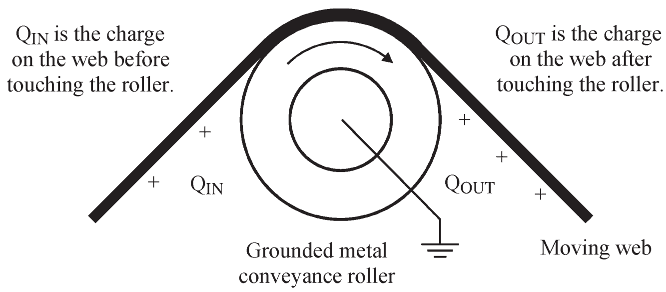

Fig. 3. Electrostatic charge is deposited on the surface of a web whenever it touches a chemically dissimilar material such as a metal conveyance roller. More charge is separated by materials that are farther apart on the triboelectric series.

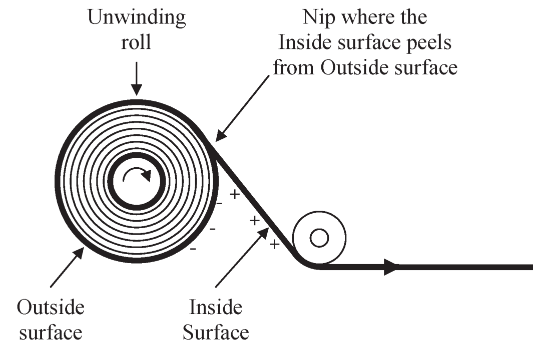

Fig. 4. One surface of the web is often chemically different from the other surface due to coatings or laminates of different materials. When multiple passes through an RtR manufacturing process are required, triboelectric charging can occur between the surfaces in the wound roll. When the surfaces separate at the unwinding nip, substantial static charging can occur.

attracted dust to motion-picture film [6]. Photographic-film manufacturing has been notoriously sensitive to electrostatic issues because of the product's sensitivity to light from electrostatic discharges. Many of the emerging applications suffer from electrostatic problems because they are sensitive to dust contamination, use flammable solvents, or involve the production of electronic components. The separation and accumulation of electrostatic charge during manufacturing can cause defects in the product and increase waste. Electrostatic discharges can damage the product, cause erratic operation, or cause intermittent problems with process-control equipment. When flammable materials are present, sparks can ignite fires or explosions. To prevent these problems, key elements of an RtR manufacturing process include electrostatic fieldmeters permanently mounted at strategic locations along the web path and effective methods to safely dissipate static charge.

C. Sources of Static Charging

Conveyance Electrification: The deposition and accumulation of electrostatic charge on a moving web is the basis of operation of this version of a Van de Graaff generator [7] shown in Fig. 2. Similarly, in an RtR manufacturing process, electrostatic charge is deposited on the web each time the web surface touches a chemically dissimilar material [8] such as a conveyance roller, as shown in Fig. 3. The amount of charge that separates in an interaction depends upon the chemistry of the web and the chemistry of the conveyance-element's surface. More charge separates when the materials are farther apart on the triboelectric series [9]. If the web surface is sufficiently conductive, web charge will dissipate to ground through the grounded metal roller. However, if the web surface has insufficient conductivity, the charge moves too slowly toward the grounded roller to dissipate [10], [11] and static charge accumulates on the web surface. Although this charging mechanism is illustrated using a roller, any contact between the web and an object, such as a backing plate or screen, would separate charges in a similar manner.

1) *Unwinding Electrification*: Many production processes involve multiple passes through an RtR manufacturing process. For example, printing applications typically involve purchased support or web from a vendor, running this media through a printing and drying process, and finishing the product with a converting line to slit, chop, and package the final product. In this example, there are at least three passes through an RtR manufacturing process: 1) support manufacturing by the vendor; (2) printing; and (3) converting. The "master roll" or "wide roll" wound at the end of the preceding operation must be unwound at the beginning of the next operation. Static charge from previous operations may be present in the wide roll. In addition, it is very common for one surface of the web to be chemically different from the other surface due to coatings or laminates of different materials. Therefore, unwinding electrification at the nip of the unwinding stockroll, shown in Fig. 4, is an important source of static charging.
2) *Winding Stockroll Potential*: At the end of an RtR manufacturing process where the web is wound to form a large roll, a small amount of electrostatic charge that was of no consequence previously become critically important. As shown in Fig. 5, as the web winds to build the stockroll, charge accumulates, and the stockroll potential can become very high [12]. Sparks that jump to grounded objects at several feet distant have been observed. Severe shocks are a risk to automated machines or operators that unload and handle the wound rolls. Moreover, these large static discharges can produce severe damage to sensitive features of the web and, at the very least, can dramatically complicate the distribution of charge on the web, which may cause problems in subsequent production steps.

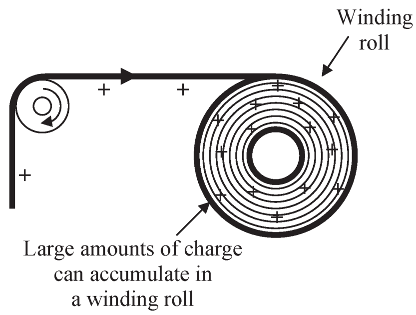

Fig. 5. Small amounts of static charge that are of no consequence earlier in the process can cause high electric potentials on the winding roll because large amounts of charge accumulate within the roll.

D. Static Monitors and Charge Dissipation Devices

1) *Electrostatic Fieldmeters*: The most versatile static monitors are electrostatic fieldmeters. Modern fieldmeters are capable of responding to low levels of static charge and are electrically stable. Some models are intrinsically safe and can be used in hazardous locations. An electrostatic fieldmeter is a key element of RtR manufacturing processes because it measures and characterizes the level of static charge present in the process.
2) *Passive Static-Dissipation Technology*: Summarized in Table I are several commercially available devices designed to dissipate static charge. These devices fall into two general categories; passive and active. The operation of passive devices depends on the electric field due to the static charge because they function by concentrating the electric field at fine points and edges and cause the air to breakdown or become ionized. Passive devices are inexpensive and can effectively dissipate high levels of static charge without external power but require a secure electrical connection to ground. Passive devices have a minimum threshold electric field required to "turn on." Consequently, when the electric field is too low or if the device is installed improperly, passive devices do not remove charge.
3) *Active Static-Dissipation Technology*: Active ionizers require external power to operate. While most of these devices use electrical power, radioactive sources use energy provided by the radioactive element. Although active devices are more expensive than passive devices, they are capable of completely neutralizing static charge, no matter how low the electric field is. Their performance is determined by the rate of ion production (ionizer design and voltage) and by how quickly these ions can move from the ionizer to the static charge (proper location).

II. Electrostatic Problem Analysis Model

RtR manufacturing processes are often complex with many component operations including, for example, unwinding, web steering, lamination, coating/printing, casting, drying or curing, slitting, trimming, and winding. Having a model or framework to organize information is most valuable when working to diagnose static problems in existing operations or when working to anticipate static issues during the design of the process or during the commercialization of products. Glor [1] proposed a very useful model in 1985 that is shown in Fig. 6 to include issues in RtR manufacturing operations.

Static charge is separated whenever two chemically dissimilar surfaces touch and separate, as shown in Fig. 1. The triboelectric series [9] provides guidance for determining how much surface charge results from the contact between two surfaces. Many factors are important in determining the charge, including material selection, surface roughness, contact pressure, material compliance, contact time, slipping or micromotion between the surfaces, and surface contaminants. Intimacy of contact is the overarching issue. Higher charge is separated by contacts with greater surface intimacy, i.e., greater area and higher pressure. Usually, only a small amount of charge results from a single contact. However, in certain circumstances where surfaces are compliant and pressures are great enough, such as in pinch roller, a sufficient amount of charge can be separated by a single contact to cause static problems [13]. Compliant pinch rollers are commonly used in web cleaners, drive rollers, and in gravure printing.

Following charge separation, the next step in the model shown in Fig. 6 is charge movement or transport. In an RtR manufacturing process, the web carries charge as it is transported through the machine. This movement or transport enables charge to accumulate on the web, on insulating surfaces that touch the web such as rubber-covered rollers, and within the winding stockroll at the end of the process.

Shown in Fig. 6 are three consequences of charge accumulation. In a well-designed process, charge dissipates harmlessly to ground. Otherwise, the high electric field results in sheet sticking or jamming, coating nonuniformities or defects, or dust attraction and contamination. The accumulated charge can also result in a discharge or spark with sufficient energy to ignite fires or explosions. Sparks and discharges can also damage electronic components, cause electromagnetic interference, or result in erratic operation of process-control equipment by resetting machine logic.

III. Discussion

Three important insights may be gleaned from the electrostatic model shown in Fig. 6.

1) Charge separation is minimized by proper material selection during product development and process design. Alternatively, electrical conductivity at the site of charge separation (surface conductivity) can dissipate the charge.
2) Charge movement or transport offers an opportunity to measure the charge using online static monitors and apply well-established statistical process control methodology to anticipate the onset of static problems.
3) The charge-dissipation technologies summarized in Table I should be targeted at locations where charge accumulation is high to be most effective.

A. Charge Separation

The effort to minimize charge separation in an RtR manufacturing process begins at designing the production process and

TABLE I
SUMMARY OF COMMERCIALLY AVAILABLE CHARGE-DISSIPATION TECHNOLOGY

Description	Type	Cost	Performance/Comments
Tinsel	Passive	Low	Sufficient to suppress sparks and lower dust attraction. No external power is needed. Ineffective at low levels of charge. Performance can degrade quickly with time as tinsel strands become matted
Static String™, Static Elastic™ [24]	Passive	Low	Sufficient to suppress sparks and lower dust attraction. No external power is needed. Ineffective at low levels of charge. More robust that tinsel.
Ionizing Air Blower	Active	Medium	Intended for applications where parts have a long residence time in the airflow (e.g. electronic work stations). Can dissipate low levels of charge. Devices can have a long life with periodic maintenance.
Shockless Pin Array Ioinizer	Active	Medium	Intended for use in solvent rated areas or where there is a possibility that a person could touch an ionizing pin. Relatively high ion output. Devices can have a long life (years) with periodic maintenance.
High Output Pin Array Ionizer	Active	Medium	Intended for high speed (short residence time) applications. Depending on the geometry, ionizers can be located some distance (several feet) from charge to be dissipated. Devices can have a long life (years) with periodic maintenance.
Radioactive Source	Active	High	Alpha and Beta emitters are commercially available. No external power is needed. Intended for applications where external power and/or light is not permitted. Regulatory compliance and regular inspections are burdensome.
Corona Wire Ionizer	Active	High	Highest performance in terms of ion output and uniformity. Used extensively in photocopiers. Regular maintenance and cleaning are essential to maintain performance.

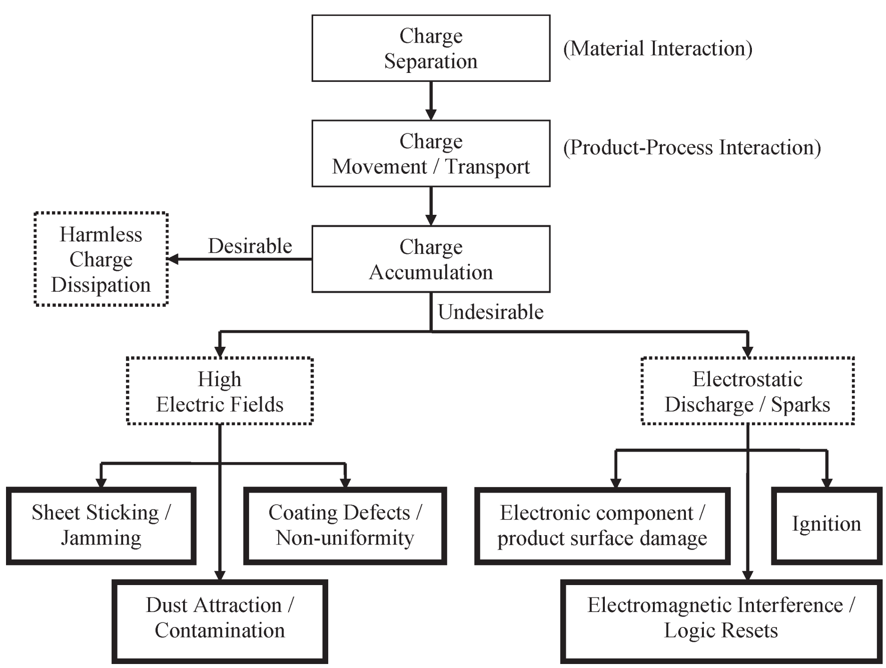

Fig. 6. Glor's model [1] for the separation, accumulation, and dissipation of electrostatic charge is extended to include issues and consequences in RtR manufacturing processes.

the products to be produced. Selecting or designing materials to minimize charge separation is an important design constraint. In the long run, this is by far the most cost-effective means to solve static issues. A process designed using compatible materials requires no additional charge-dissipation technology and no maintenance of these devices. Material selection should be guided by experimental measurements of contact charging or tribocharging. These measurements may be made using commercially available Faraday cups and nanocoulomb meters. Benchtop or full-system test protocols must be developed to simulate the contact, separation, and charging that occurs in the process. Measurements must be sufficiently repeatable to

TABLE II
SOURCES OF VARIABILITY IN CHARGE LEVELS DURING RTR MANUFACTURING OPERATIONS

Source of Variability	Comments	Countermeasure
Machine conditioning	Conditioning is the transfer of surfactants or other materials present on the surface of the web onto the machine rollers and belts. This is especially important at changeovers between different products.	Clean machine rollers and belts.
Machine set-up & maintenance	Adjustments such as pinch roller nip pressure, roller alignment, and belt tension affect the amount of static charge separated during operation.	Use written procedures and set-up jigs to insure consistent machine operation.
Machine environment	The relative humidity and temperature during operations may affect charge levels.	Monitor RH and control RH if necessary.

rank-order candidate materials and enable the selection of compatible materials or formulations.

In addition, attention should be given to the details of the contact between the web and conveyance members. For example, drives that use high-pressure compliant pinch rollers should be avoided, if possible. If pinch rollers are needed, minimize the contact area between the pinch roller and the product by using less compliant rubber and minimal contact pressure. The roughness of all surfaces that contact the web should be considered since, generally, rougher surfaces produce less real contact area than smooth surfaces and therefore cause reduced charge separation, all other factors being constant.

Electrical conductivity is an important charge-dissipation technology that should be designed into the production process and products to be produced. Volume conductivity has an astonishingly broad range from 10^{+7} S/m for metal to 10^{-22} S/m for insulators. Within this range of 10^{+29} S/m, (1) provides guidance, accurate to perhaps a factor of three, for selecting the conductivity σ_{VOL} of rubber- or polymer-covered rollers by requiring that charge dissipate within about one roller revolution

$$\sigma_{\mathrm{VOL}} = 3\kappa\varepsilon_0 \frac{U}{\pi D}. \quad (1)$$

Charge dissipates in a time characterized by the charge relaxation time [14]. A higher conductivity is needed for a higher process speed U and for a smaller roller diameter D [15]. The permittivity of free space ε_0 is approximately 9 pF/m, and the dielectric constant κ of rubber or polymer is typically in the range of from two to eight. Therefore, for a process operating at 1 m/s with a 10-cm (4-in)-diameter roller, a rubber or polymer covering must have a conductivity exceeding about 40 nS/m or a volume resistivity ρ_{VOL} of less than about $2 \times 10^{+9}\ \Omega \cdot \mathrm{m}$. The volume resistivity of existing rollers should be measured using an insulation tester, which is a megohmmeter capable of detecting resistances of $2 \times 10^{+12}\ \Omega$ (2 TΩ), which typically operates in the range 500 V–10 kV.

Electrical conductivity can also be designed into the product to be manufactured typically by including a conductive coating on the backside of the product. While the conductive coating provides excellent static protection for the continuous web during the RtR manufacturing process, the impact of this coating on customer applications should be evaluated. For example, if the product is to be finished into cut sheets, the conductive coating can cause electrostatic sticking [16]. There are many electrically conductive materials suitable for coating processes that are commercially available [17]. One of the oldest classes of materials used to provide ionic conductivity are quaternary ammonium salts [18]. The required surface electrical resistivity should be determined experimentally, although values are commonly in the range 10^{+8}–$10^{+12}\ \Omega/\square$. While the proper units of surface electrical resistivity are ohms, the practical units of ohm per square have been widely adopted to distinguish between electrical resistance measured in ohms and the measurement of surface resistivity that includes the measurement geometry [19]. The surface electrical resistivity should be measured using electrodes designed to measure surface resistance at voltages ranging from 1 V to 1 kV.

B. Static Monitors

In an RtR manufacturing process, the electrostatic charge is typically transported through the process by an insulating web. Charge accumulates on the web and on the winding roll at the end of the process. Electrostatic fieldmeters can be positioned along the web path to measure the electric field resulting from the static charge. The measurement locations must be chosen properly to obtain reliable readings [20]. For electrically insulating webs, the surface-charge density can be inferred from the electrostatic-fieldmeter measurements [21], [22]. Data from permanently mounted fieldmeters can be analyzed using control charts [23] to determine whether the process is in control. Control charts of the output of fieldmeters can be used to detect variations in charge levels caused by assignable causes such as those summarized in Table II. The assignable cause must be identified and remedied to prevent generation of waste.

To help identify the assignable cause for high static readings, a portable electrostatic fieldmeter can be used to measure the electric field along the web path of a production machine during operation. These data form a static survey of the machine that is much more detailed than information from permanently mounted monitors. The static survey locates areas where the static-charge levels are high, which helps identify the assignable cause for high static. When using a portable electrostatic fieldmeter, it is often important to determine the static surface charge-density on the web from the fieldmeter readings. Careful analysis is required to interpret these readings [21], [22] because the electric field depends on the measurement geometry in a complex way. Field solver software may be used to obtain reliable estimate of surface charge-density [21].

C. Static-Dissipation Technology

When the high static areas of an RtR manufacturing process have been identified, the first countermeasures are to investigate the machine setup and material-selection alternatives. Once these options have been exhausted, static-dissipation technologies should be considered. Passive devices such as tinsel, Static String [24], or conductive brushes are the first choice since they are effective and inexpensive. In critical applications where the charge must be nearly completely neutralized, however, active ionizers must be used. In most RtR applications, pin-array ionizers are used to dissipate static charge, and corona wire ionizers are used primarily in photocopiers, imaging applications, and critical coating applications where the surface charge-density must be precisely controlled [25], [26].

IV. Conclusion

Following is the summary of what has been presented and discussed in this paper.

1) An existing model for charge separation and accumulation is extended to include common issues in RtR manufacturing operations.
2) From this extended model, it is apparent that static monitors can measure the charge present in a manufacturing process.
3) The electrical conductivity of rubber- or polymer-covered roller should be sufficiently high to permit charge to dissipate in one roller revolution; $\sigma_{\mathrm{VOL}} > (3\kappa\varepsilon_0 U)/(\pi \mathrm{D})$.
4) High static levels resulting from assignable causes can be identified by control charting the readings from permanently mounted electrostatic fieldmeters.
5) Areas of high electrostatic field are best identified from a static survey of portable electrostatic-fieldmeter measurements along the web path during the operation of an RtR manufacturing process.
6) Charge-dissipation technology is most effective when used at locations where charge accumulates.

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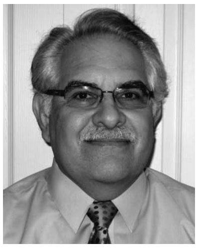

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