Comparative Fatigue Lives of Rubber and PVC Wiper Cylindrical Coatings

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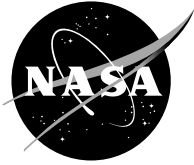- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

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Abstract

Three coating materials for rotating, cylindrical, coated wiping rollers were fatigue tested in two Intaglio printing presses. The coatings were a hard, cross-linked, plasticized polyvinyl chloride (PVC) thermoset (P-series); a plasticized PVC (A-series); and a hard nitrile rubber (R-series). Both two- and three-parameter Weibull analyses and a cost-benefit analysis were performed. The mean value of life for the R-series coating is 24 and 9 times longer than that of the P- and A-series coatings, respectively. At a very high probability of survival, the R-series coating is approximately 2 and 6 times the lives of the P- and A-series, respectively, before the first failure occurs. The cost and replacement rate for the R-series coating is significantly less than those for the P- and A-series coatings. When all coatings are run to failure, using the mean (life) time between removal (MTBR) for each coating to calculate the number of replacements and costs provides qualitatively similar results to those using a Weibull analysis. The relationship suggested between glass transition temperature and life is that the closer the glass transition temperature to the operating temperature, the lower the associated predicted life.

Nomenclature

F	statistical percentage of failed specimens
G'	storage modulus, Pa (psi)
G''	loss modulus, Pa (psi)
L	life, stress cycles or impressions
L_β	characteristic life or life at which 62.3 percent of population fails
L_μ	location parameter; time below which no failure occurs, cycles
L_{10}	life at which 10 percent of total specimens have failed
L_{50}	life at which 50 percent of total specimens have failed
m	slope of Weibull plot
S	survivability

ΔT difference between operating temperature and glass transition temperature, °C (°F)

T_g glass transition temperature, °C (°F)

t time, s

γ shear stress, Pa (psi)

δ angle at which stress and strain sinusoidal curves are out of phase in dynamic analysis, deg

$\tau(t)$ time-dependent strain, Pa (psi)

ω angular frequency, rad/s

Subscript:

o initial

Introduction

Intaglio printing is used in high-quality applications where a desired texture is also imparted to the finished print product along with the ink. In this printing process, ink is applied to the entire surface of the printing plate, although ink is ultimately desired only in the engraved valleys of the plate. The excess ink on the flat plateaus between the engraved valleys must be removed before transfer to the printed product. The paper is squeezed against the plate with such force that ink is transferred from the capillary-like engraved lines, causing the surface of the paper to become textured and/or deformed.

A coated wiper cylinder is used as a wiping roller to remove the excess ink from the printing plates. The wiper rotates and oscillates from side to side as excess ink is removed from the printing plate surface before impressions are made. On press, the wiping roller is half submerged in a tank of caustic solution at a temperature of 60 °C (140 °F). In the tank, ink is removed chemically and physically by brushes and blades from the surface of the wiper.

Microscopic and visual inspection of failed wiper surfaces show that the primary mode of failure is fatigue. Fields of cracks 10 to 30 µm (3.9×10^{-4} to 1.2×10^{-3} in.) wide and 100 to 300 µm (3.9×10^{-3} to 1.2×10^{-2} in.) long form on the surface of failed coatings. Figure 1 is a micrograph of a failed wiper
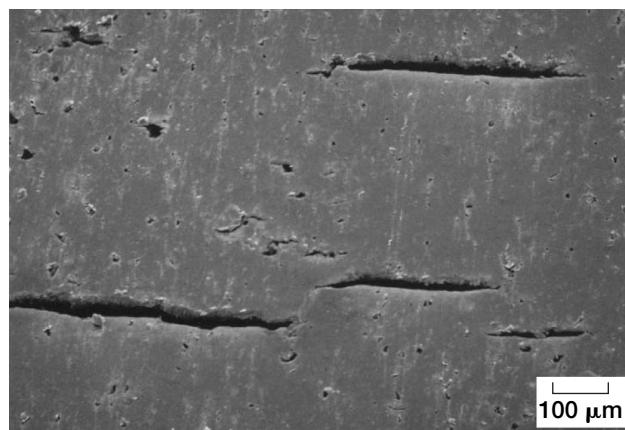

Figure 1.—Fatigue cracks on surface of failed P-series
wiper roller coating after 100 000 impressions.

coating surface shown at a magnification of 100. Excess ink that has become entrapped in the fatigue cracks is transferred to the printing plates, imprinting the fatigue crack images on the finished product. The failure criterion is artistically driven and is based upon the appearance of the printed product. Thus, wipers are not removed at the first appearance of fatigue cracks on the surface of the wiper coating, but at the first visual appearance of a crack image transferred to the printed product.

A program was undertaken (1) to determine the endurance of the roller coatings based upon a fatigue criterion. The standard coating used was manufactured in-house by the user and was a hard, cross-linked, plasticized polyvinyl chloride (PVC) thermoset. The candidate replacement coating was a softer plasticized PVC. A total of 447 tests was conducted with these coatings in a production facility. The data were evaluated using a two-parameter Weibull analysis. The softer coating produced over twice the life of the harder cross-linked coating. Using the softer coating reduced the wiper replacement rate by two-thirds, resulting in minimum production interruption (1).

As a followup to this program, a hard rubberized coating was evaluated together with the two plasticized PVC coatings reported by Vlcek, Hendricks, and Zaretsky (1). However, the followup program used different presses, ink, and printing plates for the obverse side of the job reported in Ref. (1). The primary objectives of the research reported herein were to use both two- and three-parameter Weibull analyses to determine (a) the fatigue life of each of the three coatings studied, (b) the minimum time below which there was no probability of failure, and (c) the rate and cost of coating replacement due to failure.

Weibull Statistical Method

In 1939, Weibull (2–4) developed a method and an equation for statistically evaluating the fracture strength of materials based upon small population sizes. This method can be and has been applied to analyze, determine, and predict the cumulative statistical distribution of fatigue failure or any other phenomenon or physical characteristic that manifests a statistical distribution. The dispersion in life for a group of homogeneous test specimens can be expressed by

$$\ln \ln \frac{1}{S} = m \ln \left(\frac{L - L_\mu}{L_\beta - L_\mu} \right); \quad L_\mu \langle L \langle \infty \tag{1}$$

where S is the probability of survival as a fraction ($0 \le S \le 1$); m is the slope of the Weibull plot; L is the life (stress cycles); L_μ is the location parameter or the time (cycles) below which no failure occurs; and L_β is the characteristic life (stress cycles).

The format of Eq. (1) is referred to as a three-parameter Weibull analysis. For most if not all failure phenomenon, there is a finite time period under operating conditions when no failure will occur. In other words, there is a zero probability of failure, or a 100-percent probability of survival, for a period of time during which the probability density function is nonnegative. This value is represented by the location parameter L_μ. Without a significantly large data base, this value is difficult to determine with reasonable engineering or statistical certainty. As a result, L_μ in Eq. (1) is usually assumed to be zero and can be written as

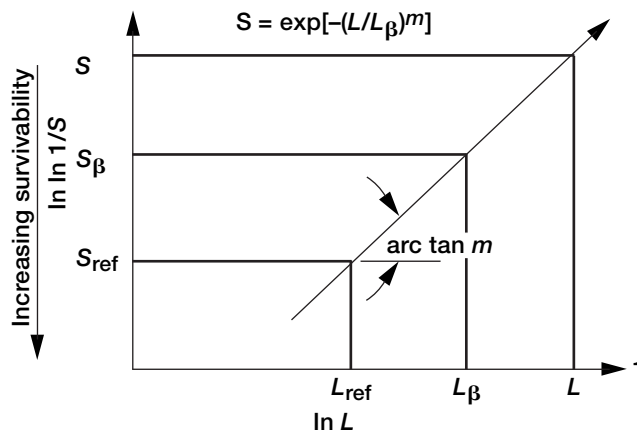$$\ln \ln \frac{1}{S} = m \ln \left(\frac{L}{L_\beta} \right); \quad 0 \langle L \langle \infty \tag{2}$$

Figure 2.—Weibull plot *m*, Weibull slope or tangent of
line; S_β, probability of survival of 36.8 percent at which
$L = L_\beta$ or $L/L_\beta = 1$ (From Ref. 5).

This format is referred to as the two-parameter Weibull distribution function. The estimated values of *m* and L_β for the two-parameter Weibull analysis are not equal to those of the three-parameter analysis. As a result, for a given survivability value *S*, the corresponding value of life *L* will be similar but not necessarily the same in each analysis.

By plotting the ordinate scale as ln ln (1/*S*) and the abscissa scale as ln *L*, a Weibull cumulative distribution will plot as a straight line, which is called a "Weibull plot." Usually, the ordinate is graduated in statistical percent of specimens failed *F* where $F = [(1 - S) \times 100]$. Figure 2 is a generic Weibull plot with some of the values of interest indicated. The derivation of the Weibull distribution function can be found in (5).

The Weibull plot can be used to evaluate phenomena that result in a statistical distribution. The tangent of the resulting plot, called the "Weibull slope" and designated by *m*, defines the statistical distribution. Weibull slopes of 1, 2, and 3.57 represent exponential, Raleigh, and Gaussian (normal) distributions, respectively. In 1947, Lundberg and Palmgren (6) were the first to use Weibull analysis to predict the lives of rolling-element bearings.

The statistical method for plotting and evaluating data using Weibull analysis was developed by Johnson (7, 8). It is assumed that a straight line is representative of the data, even though in many cases the data loci are not linear. Using the method of least squares, a straight line is drawn through an array of points on each plot. From this straight line, two significant lives are obtained for comparison: these are the lives at which 10 and 50 percent of the specimens have failed and are designated L_{10} and L_{50}, respectively. The failure index given with each plot indicates the number of failed specimens of those tested. The confidence number is a comparison of the repeatability of the test results and is dependent on the number of failures in each group of specimens, the ratio of the lives being compared, and the Weibull slope of each group. A confidence number of 90 percent indicates that 90 out of 100 times the qualitative results would be the same if the tests were to be repeated.

From the Weibull plot, the values of m and L_β are determined. With these values known, it is possible to determine the failure rate for any time increment from Eq. (2). Also, if the location parameter L_μ is known, it is possible to determine the failure rate for any time increment from Eq. (1).

The first effort to determine the location parameter L_μ for rolling-element fatigue data was reported in 1962 by Tallian (9, 10) and subsequently by others for rolling-element bearings (11–13). Tallian used a two-parameter Weibull analysis (9) and more than 2500 data points. His study suggested that the location parameter occurs at a probability of survival of 99.9 percent. More recently, Shimizu (14) found that at very high probabilities of survival, fatigue data best fit a log-normal distribution. He determined the location parameter L_μ to be the life at the 99.9-percent probability of survival. The location parameter was then substituted into the three-parameter Weibull life distribution function (Eq. (1)). Shimizu' method (14) was used to analyze the data presented herein.

Specimens and Procedure

Materials

Three wiper coating materials (P-, A-, and R-series) were evaluated in production. Both P- and A-series materials were plasticized PVC plastisols that were applied by blade-coating techniques to steel cores rotating in a Plastirota oven. Although the user manufactured both PVC coatings in-house, the third coating evaluated (R-series) was obtained from an outside supplier. All three wiper coating material surfaces were machine finished to a high gloss on a lathe. The coating materials were used on an Intaglio press to produce the obverse (front) side of a printed surface.

The P-series coating was in use at the beginning of this study, but a replacement was being sought. The P-series coating was a cross-linked, plasticized PVC thermoset formed from a plastisol of polyvinyl chloride resin, a polyfunctional acrylic monomer (TMPTMA), dioctyl phthalate plasticizer, carbon black, and calcium chloride. Crosslinking was chemically initiated by t-butyl peroxybenzoate initiator and was driven by high fusing temperatures (180 °C or 356 °F). The plasticized PVC and the cross-linking monomer both contribute to the characteristics of the final material, which had a Shore D hardness of 45.

The viscoelastic behavior of laboratory-prepared samples of P-series coating material was characterized using dynamic mechanical analysis (DMA) (15–17). In this technique, an oscillatory stress (1 Hz sinusoidal) is applied to a sample of known geometry as the temperature is incrementally increased (2 °C/min or 3.8 °F/min). If the material were perfectly elastic, the strain would be completely in phase with the applied stress; however, if the material behaves in a Newtonian manner, the strain is 90° out of phase with the stress. For plastics that fall between these extremes, as a result of the viscous dissipation or loss of energy and elastic storage of energy, the strain exhibits a phase shift with respect to the applied stress. Time-dependent strain can be defined in terms of in-phase and out-of-phase components of stress:

$$\tau(t) = \gamma_o \left[G'(\omega)\sin\omega t + G''(\omega)\cos\omega t \right] \tag{3}$$

where $\tau(t)$ is the time-dependent strain; γ_o is the initial stress; $G'(\omega)$ and $G''(\omega)$ are the storage and loss modulus, respectively; ω is the angular frequency; and t is the time. The storage modulus is given by

$$G'(\omega) = \frac{\tau_o \cos\delta}{\gamma_o} \tag{4}$$

where δ is angle at which stress and strain sinusoidal curves are out of phase in dynamic analysis (15–17). The loss modulus is given by

$$G'' = \frac{\tau_o \sin \delta}{\gamma_o} \tag{5}$$

The tan δ will be used to identify the glass transition temperature T_g (temperature of the peak of the tan δ curve) and the relative extent of crosslinking (breadth of the tan δ curve (16–19)). The tan δ is the ratio of the storage and loss moduli:

$$\tan \delta = \frac{G''(\omega)}{G'(\omega)} \tag{6}$$

DMA thermal analysis techniques were used to determine the following properties of laboratory-prepared samples of P-series coating material: glass transition temperature, 39 °C (102 °F); storage modulus at 60 °C (140 °F), 5.56×10^6 Pa (806 psi); and loss modulus at 60 °C (140 °F), 1.64×10^6 Pa (238 psi). The glass transition temperature was reported as the peak of the curve of tan δ versus temperature. The loss and storage moduli were reported as the respective values at the operating temperature of the wiper.

Because fatigue cracking was the primary mode of P-series material failure, a modification to the material was sought so as to minimize the tendency of the material to fatigue failure and cracking. The two obvious approaches were to change the PVC plasticizer concentration or to change the crosslinking of the acrylic monomer (20).

The material properties of plasticized PVC vary greatly with plasticizer concentration. Lightly plasticized PVC is very hard and rigid, as exemplified by white PVC plumbing pipe. However, as plasticizer is added, the resulting material becomes as flexible as a child's squeeze toy.

The monomer is the other primary material in the P-series coating material. When catalytically cross-linked and exposed to heat, the monomer is an extremely brittle solid. A honeycomb structure forms as air bubbles are entrapped in the solid. Very little pressure applied by a finger will cause this material to crack and powder, as can be observed in samples of monomer and catalyst exposed to a range of temperatures in a convection oven. When mixed with the plasticized PVC, however, the bubbles and honeycomb structure are not visible, but the characteristics of the combined material (20) are those of a material more brittle than the plasticized PVC alone.

Two options of changing the material characteristics of the polymerization process were explored in the laboratory. Both fusing temperature and initiator (t-butyl peroxybenzoate) concentration were examined. Samples of P-series plastisol were fused in the laboratory at 130, 145, 155, 160, and 185 °C (266, 293, 311, 320, and 365 °F). DMA temperature scans were performed on each of the five samples, and the resulting tan δ peaks are shown in Fig. 3. Note that with increasing temperature from 130 to 155 °C (266 to 311 °F), the glass transition temperature shifts to the left. Because the peaks at 160 and 185 °C (320 and 365 °F) are effectively the same, no additional curing is driven by increasing the processing temperature above 160 °C (320 °F).

Polymers exhibit five distinct regions of physical behavior with increasing temperature (15, 17). Below the glass transition temperature, polymers are typically classified as brittle. As the temperature of the polymer increases, molecular motion increases, and the material enters a leathery region at about the
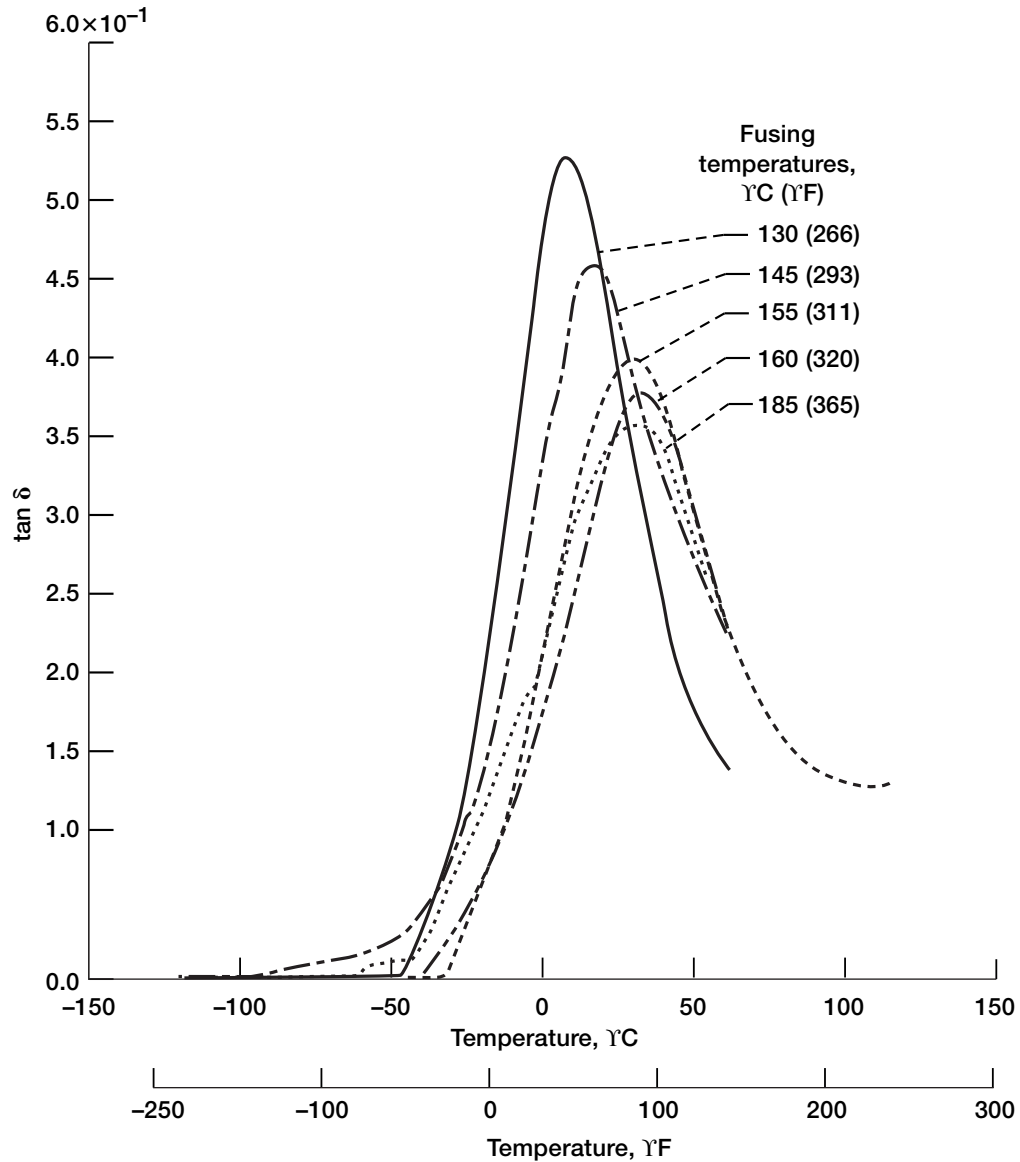
6.0×10⁻¹

6.0×10^{-1}

5.5

5.0

4.5

4.0

3.5

tan δ 3.0

2.5

2.0

1.5

1.0

0.0

Fusing
temperatures,
ϒC (ϒF)

130 (266)
145 (293)
155 (311)
160 (320)
185 (365)

−150   −100   −50   0   50   100   150

Temperature, ϒC

−250   −100   0   100   200   300

Temperature, ϒF

Figure 3.—Dynamic mechanical analysis (DMA) tan δ temperature scans of P-series plasticized PVC-monmer plastisols fused in laboratory at five temperatures.

glass transition temperature. With increasing temperature comes the rubbery plateau, followed by rubbery flow and liquid flow. The brittle and leathery transition should be familiar to anyone who has tried to fold a plastic tarp in the winter when the material is cold, stiff, and brittle. In the summer, the warm plastic easily folds.

Since it was desirable to have a material less brittle than the P-series coating at the operating temperature, less monomer crosslinking or a lower glass transition with respect to the operating temperature was a preferred change. Laboratory samples were prepared with decreasing amounts of initiator and as expected, both the glass transition temperature, as determined by DMA analysis, and the hardness decreased with decreasing initiator concentration (Table 1).

TABLE 1.—CHANGES IN GLASS TRANSITION
TEMPERATURE AND HARDNESS WITH
INCREASING MONOMER CROSS-LINKING
INITIATOR CONCENTRATION

Cross-linking initiator t-butyl peroxybenzoate, percent of concentration[a]	Glass transition temperature, T_g, °C (°F)	Hardness, Shore D
0.00	8.3 (46.9)	38
0.10	8.5 (47.3)	42
0.25	21.3 (70.3)	51
1.00	27.0 (80.6)	57

[a]Percent of initial concentration in P-series formulation.

As a result of the foregoing observations and screening tests (not reported herein), the P-series material was replaced by the A-series material, which was formulated, scaled up, and evaluated in production. Like the P-series coating, the A-series material is also formed from a plastisol of dioctyl phthalate plasticized PVC resin. While the polyfunctional acrylic monomer (TMPTMA) is present, crosslinking to a lesser degree is assumed because it is driven by temperature alone (180 °C or 356 °F) and is not chemically initiated. The lighter cross-linked monomer in this system is flexible and bends when finger pressure is applied. This flexibility can be observed in samples of monomer that are exposed to a range of temperatures in a convection oven. As a result, this softer plasticized PVC-monomer-system coating material has a Shore D hardness of 28. Graphite and calcium carbonate are also present as filler materials. The glass transition temperature of the laboratory-prepared samples is 8 °C (46 °F); the storage modulus at 60 °C (140 °F) is 2.84×10^6 Pa (412 psi); and the loss modulus at 60 °C (140 °F) is 4.51×10^5 Pa (65.4 psi).

The same polyfunctional acrylic monomer (TMPTMA) is present in both the A- and P-series plasticized PVC plastisols. The crosslinking in the A-series material is driven solely by the fusing temperature, whereas the crosslinking in the P-series material is driven by both chemical initiation (t-butyl peroxybenzoate catalyst) and the fusing temperature. As a result, P-series material should be a stiffer, harder material with more crosslinking. It can be deduced from the breadth and position of the DMA glass transition peaks (Fig. 4) of these two materials that this is indeed the case (16–19). The glass transition temperature of 39 °C (102 °F) for the P-series material is greater than the temperature of 8 °C (46 °F) for the A-series material. The peak associated with the P-series material is clearly broader than that of the A-series material (Fig. 4). As the number of crosslinks increases, the glass transition occurs over a broad range of temperatures.

The A- and P-series coating materials are PVC-based materials, and thus a typical Poisson ratio of 0.4 is assumed. Based upon loss and storage modulus data determined from a DMA thermal analysis of laboratory-prepared samples, the modulus of elasticity of the A-series material at 60 °C (140 °F) was determined to be 2.88×10^6 Pa (417 psi) and that of the P-series material was 5.791×10^6 (840 psi). Although these values at first glance may seem to be low to someone working with more traditional engineering materials, they are in line with values reported in the literature for the modulus of elasticity of plasticized PVC, which ranges from 0.3 to 1.9×10^7 Pa (435 to 2900 psi) (21).
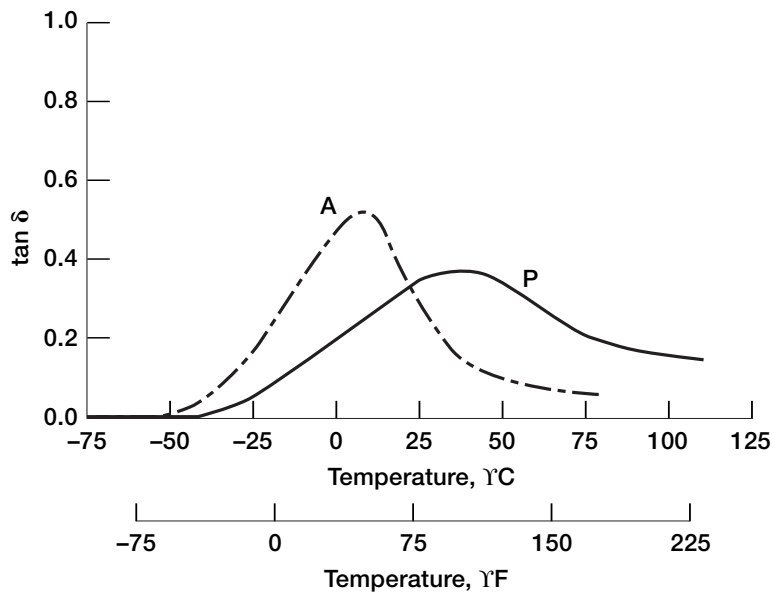
Figure 4.—Dynamic mechanical analysis (DMA) tan δ temperature scans of P- and A-series coating materials.

The R-series coating is a commercially purchased, hard nitrile rubber coating applied to similar roller cores used with the P- and A-series coatings. The coating is applied to the core in an autoclave process and is then machine-finished to a high gloss. The finished roller coating has a Shore D hardness of 55. Although the glass transition temperature of this material was not determined, the value for nitrile rubbers in the literature ranges from −38 to −2 °C (−36.4 to 28.4 °F) (22). Also, based upon the literature, the rubber coating is assumed to have a modulus of elasticity of 2.75×10^7 Pa (4000 psi) and a Poisson ratio of 0.5 (22–24).

Coated wiper rollers have a total finished diameter of 26.67 cm (10.5 in.). The replaceable coatings are applied to steel cores approximately 22.86 to 24.13 cm (9.0 to 9.5 in.) in diameter. The R-series coating is a homogeneous material for the entire thickness whereas the P- and A-series coatings are a three-layer system of two different materials. The base and top layer material are the same PVC-monomer system reported above; however, the center layer is a softer, more heavily plasticized PVC. Each of the three layers is approximately equal in thickness. The top layer of each of the wipers is polished to a high gloss.

Test Method

The test method was driven by production printing practices; therefore, all data were collected in a large-scale printing facility using unmodified commercial Intaglio printing presses during regular production runs. Figure 5 is an end-view schematic of the primary components of an Intaglio printing press. Ink is applied over the entire surface of the plate cylinder. The wiping roller removes excess ink from the flat surfaces of the engraving, whereas the ink to be transferred to the paper is left behind in the engraved lines of the plates. Presses were operated almost continuously for three 8-hr shifts, making 8000 impressions per hour.
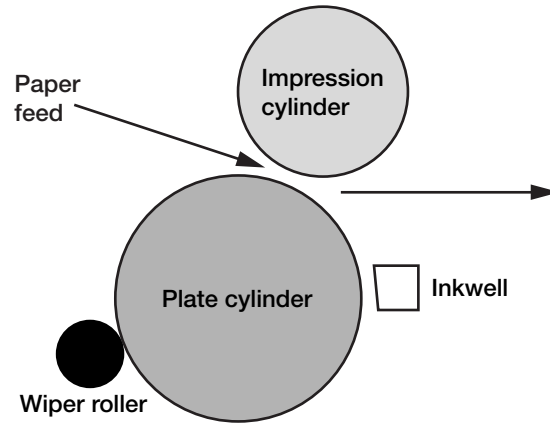
Figure 5.—End view of primary components involved in the Intaglio printing process.

The applied load is a variable that is artistically driven by the printing process. Pressmen turn two setscrews that force the wiping roller against the printing cylinder. When excess ink is removed, as indicated by blank or faded regions on the finished product, either setscrew is turned out until the desired image intensity is achieved. Thus, the optimum "wiping" setting is determined artistically.

Although the applied load to the wiping roller was never experimentally determined in production, the authors assumed a value of 1335 N (300 lb) for comparison. All wipers were run to failure or until damaged. The failure criterion was defined in production as the first appearance of errant ink on the finished product, not the first appearance of a defect on the wiper surface. Even though the definition differs from the traditional way of defining failure at the first appearance of damage, this failure criterion was consistently applied in production.

The three wiper coatings (P-, A-, and R-series) were evaluated as part of the normal production usage dedicated to printing the obverse side of a product. Wipers were removed from the press at the discretion of the operator when errant ink appeared on the finished product or the wiper was physical damaged. The wiper coatings were inspected upon removal and the coating was removed so that the steel core could be recoated. The wiper cores that could not be refurbished were repaired or discarded. Only those coatings that were removed for fatigue were deemed failures. For the purpose of statistical analysis, all other removals were considered suspensions.

For this study, 142 A-series wiper coatings were evaluated over a 9-month period on two obverse (front) presses. Sixteen P-series and eight R-series coated wipers were evaluated on the same two obverse presses during the same time period. Data were collected from three shifts during regular production printing.

Results and Discussion

Weibull Analysis

Rotating, cylindrical, coated wiping rollers used in Intaglio printing fail primarily because of fatigue or misuse. Three wiper coatings that are used on press to produce the obverse side of a printed product

were evaluated in a production facility. The standard coating used was a hard, cross-linked, plasticized PVC thermoset designated P-series. A candidate replacement coating was a softer plasticized PVC designated A-series. A second replacement coating, which was rubberized and designated R-series, was also evaluated in production. The results of these tests were compared with those reported in (1) for the P- and A-series wiper coating data obtained from six printing presses dedicated to printing the reverse side of a product (1). In the present study, both two- and three-parameter Weibull analyses were performed and the results compared. The location parameter L_μ for the three-parameter Weibull analysis was determined using the method of Shimizu (14).

The results of the P- and A-series coatings from (1) are shown in the two-parameter Weibull plots of Fig. 6 and are summarized in Table 2. The L_{10} life of the A-series coating was approximately 2.3 times that of the P-series. The softer, less cross-linked A-series coating produced over twice the life of the harder, greater cross-linked P-series coating. Using the softer coating reduced the wiper replacement rate by two-thirds and resulted in fewer production interruptions. The method of Johnson (8) was employed to obtain a confidence level of 99 percent (1).

The tests results and the Weibull analyses that compare the P- and A-series coatings in the current study are shown in Fig. 7 and are summarized in Table 3. In contrast to the results of (1) for a reverse side printing, the present results for this particular obverse side printing indicate that the differences between the two coatings are not statistically significant at the L_{10} life. At the L_{50} life, there is a statistical difference between the two coatings: the A-series has over twice the life of the P-series. A three-parameter Weibull analysis of the data suggested that at a very high probability of survival ($L_{0.1}$), the P-series coating might yield more than twice the life of the A-series coating before failure occurs. However, at times greater than that of the L_{10} life, the failure rate for the A-series coating will be less than that of the P-series coating. It is not uncommon for one material to have a better L_{10} life and then a worse L_{50} life in comparison with another material (5).

The R-series coating results are also shown in Fig. 7 and are summarized in Table 3. The life with this coating is superior to those of the P- and A-series coatings, as seen by its confidence number of 99 percent. The ratio of lives at the L_{10} level is in excess of seven times that of the P- and A-series
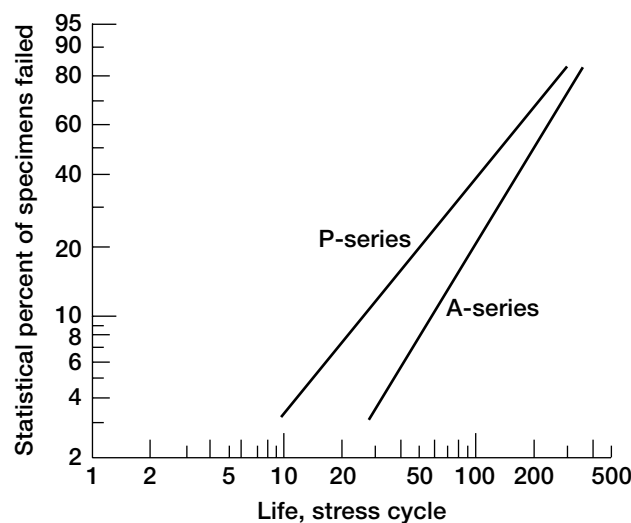

Figure 6.—Comparison of P- and A-series wiper coatings on backface of six backpresses using two-parameter Weibull analysis. Failure index: P-series, 85/104: A-series, 265/343 (data from Ref. 1).

	Wiper coating material on all backpresses	
Life,[a] stress cycles	P-series	A-series
L_{10}	25×10^3	59×10^3
L_{50}	103×10^3	194×10^3
Mean life, stress cycles	126×10^3	223×10^3
Probability of failure at mean life, percent	59	57
Weibull slope, m	1.35	1.58
Failure index[b]	85/104	265/343
Confidence number,[c] percent	--------	99

[a]Lives at which 10 and 50 percent of specimens failed.
[b]Number of failures out of total tested.
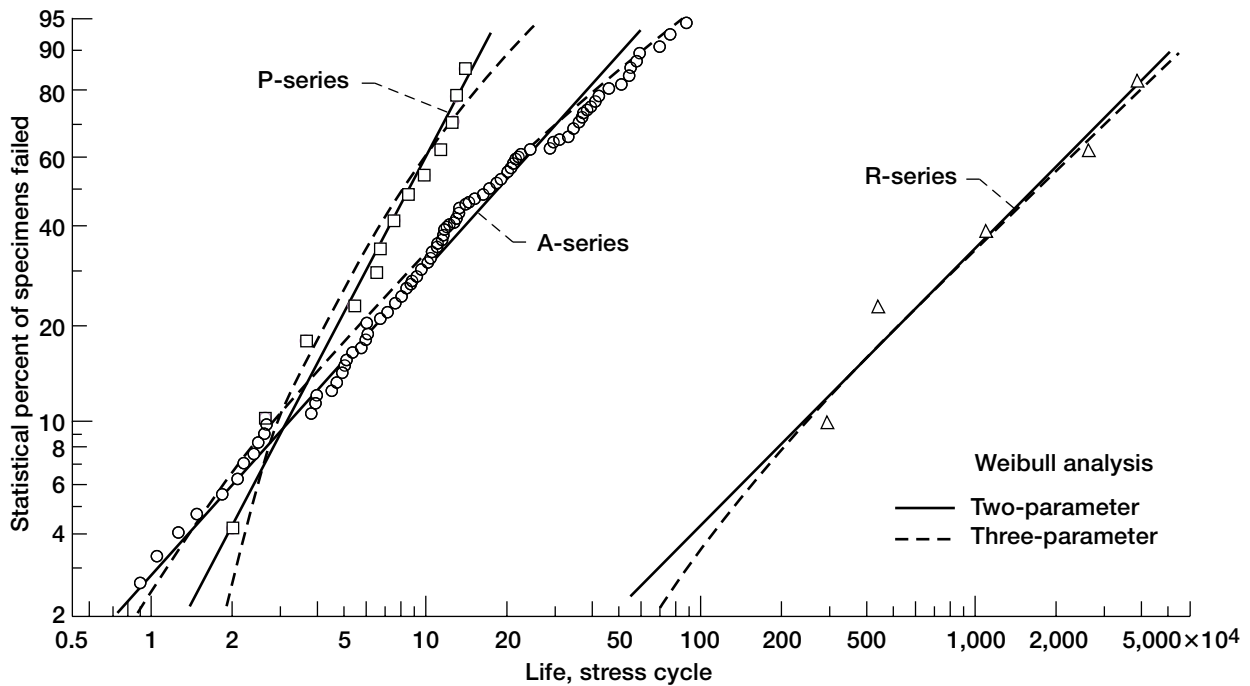[e]Percent of time qualitative test results will be same if the test is repeated.

Figure 7.—Comparison of P-, A-, and R-series frontface wiper coatings using two- and three-parameter Weibull analyses in frontpress. Failure index: P-series,13/16; A-series, 94/142; R-series, 5/8.

TABLE 3.—SUMMARY OF RESULTS FOR P-, A-, AND R-SERIES COATING DATA COMBINED FROM
TWO FRONTPRESSES USING TWO- AND THREE-PARAMETER WEIBULL ANALYSES

	Wiper coating material on all frontpresses					
	P-series		A-series		R-series	
	Weibull analysis					
	Two parameter	Three parameter	Two parameter	Three parameter	Two parameter	Three parameter
Life,[a] stress cycles						
L_{10}	31×10^3	29×10^3	32×10^3	27×10^3	240×10^3	247×10^3
L_{50}	88×10^3	86×10^3	182×10^3	189×10^3	1608×10^3	1591×10^3
Mean life, stress cycles	95×10^3	107×10^3	246×10^3	297×10^3	2340×10^3	2367×10^3
Probability of failure at mean life, percent	55.4	60.7	61.9	64.9	63.4	63.9
Location parameter,[b] L_μ, stress cycles	0	14×10^3	0	5×10^3	0	29×10^3
Weibull slope, m	1.82	1.18	1.09	0.90	0.99	0.96
Failure index[c]	13/16		94/142		5/8	
Confidence number,[d] percent	---		50		99	

[a]Lives at which 10 and 50 percent of specimens failed.

[b]Time below which no failures are expected to occur.

[c]Number of failures out of total tested.

[d]Percent of time the qualitative test results will be the same if the test is repeated.

coatings. However, using a three-parameter analysis, at the high probability of survival, the life ratio is approximately two times the life of the P-series coating and six times that of the A-series coating. For high reliability and long life, the R-series appears to be the superior coating for this application.

In Fig. 8, the coating tests from (1) are compared with those of the present study. Figure 8(a) compares the two-parameter Weibull analysis of the P-series coating. There is no statistical difference between the P-series coatings in the backface press (1) and the frontface press. However, for the A-series coatings, the L_{10} lives obtained on the frontface press are statistically significantly lower then those obtained on the backface press. The probable reasons for this life reduction were differences in the types of ink used and in the operating conditions for the two printing jobs.

Material Performance

Visual and microscopic observation of failed wiper coatings revealed a different crack growth progression before the errant ink was imprinted or transferred onto the work product. Figure 1 is a micrograph of a failed P-series surface after 100 000 impressions. Fields of multiple axially oriented cracks were observed on the surface of the wiper, although typically only one was large enough to transfer a visible defect to the finished product. A-series coatings usually failed as a result of the
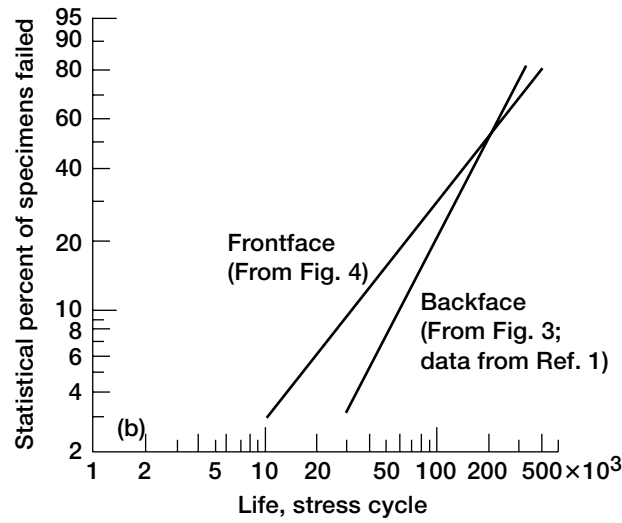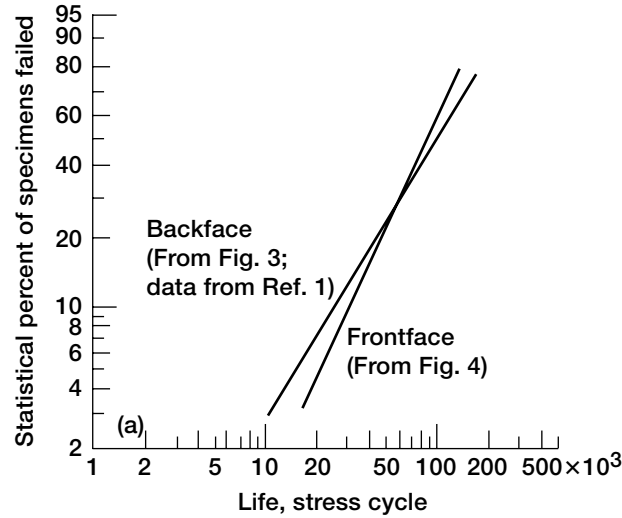
Figure 8.—Comparison of data sets for wiper coatings
for backface and frontface. (a) P-series. (b) A-series.

appearance of either significantly fewer cracks than observed in the P-series and/or a single, large surface crack or spall. The R-series wiper coatings failed typically because of the appearance of a single defect.

The maximum Hertz stress is estimated using the method of Jones (25). The wiping interface is modeled as a contact between two long cylinders of unequal diameter. One cylinder is assumed to be steel and the other, the wiper material. The wiper cylinder is 91.44 cm (36 in.) in length and 26.67 cm (10.5 in.) in diameter. The contacting cylinder is assumed to be 91.44 cm (36 in.) in diameter, and 91.44 cm (36 in.) in length. An applied load of 1335 N (300 lb) is assumed. The Hertz stress is reported in Table 4, which also summarizes the glass transition temperature, Shore D hardness, and L_{10} and L_{50} wiper lives. Based on the data in Table 4, no relationship between life and Hertz stress could be established, although at first glance, the material with the highest maximum Hertz stress would be assumed to have the shortest fatigue life. These stress levels are so low, one could argue, that the wiper surfaces should last indefinitely. In addition, Table 4 shows that no relationship appears to exist between hardness and life.

TABLE 4.—MATERIAL CHARACTERISTICS AND LIFE OF P-, A-, AND R-SERIES WIPER COATING
MATERIALS FOR TWO PRINTING APPLICATIONS IN INTAGLIO PRINTING PRESSES

Coating	Hardness, Shore D	Glass transition temperature, T_g, °C (°F)	Estimated maximum Hertz stress, Pa (psi)	Obverse side of printed product		Reverse side of printed product (data from Ref. 1)	
				L_{10} life impressions	L_{50} life impressions	L_{10} life impressions	L_{50} life impressions
P-series	45	39 (102)	1.75×10^5 (25.4)	31×10^3	88×10^3	103×10^3	25×10^3
A-series	28	8 (46)	1.23×10^5 (17.9)	32×10^3	182×10^3	194×10^3	59×10^3
R-series	55	−38.0 to −2.0 (−36.4 to 28.4)	4.04×10^5 (58.6)	240×10^3	1608×10^3	N/A	N/A

The current drawn by the press during operation was recorded during the time each of the three wiping materials was in use. This current value was used to estimate the power consumed by a particular press. Presses using A-series wipers while printing the reverse side of a product typically used 618 kW; those using P-series wipers while also printing the reverse side of a product consumed 1017 kW; those using R-series wipers while printing the obverse side of a product drew in excess of 1986 kW. It can be deduced from the current measurements and power estimates that the softer, less cross-linked wiper required less load to achieve the same degree of wiping as those required by the harder, greater cross-linked wiper and the harder rubber coating.

The glass transition temperature is an indication of a plastics change from a brittle to a leathery state with a change in temperature (15–20, 25). The glass transition temperatures of the P-, A-, and R-series coatings were 39 °C (102 °F), 8 °C (46 °F), and −38 to −2 °C (−36.4 to 28.4 °F), respectively (Table 4). Since the wiper rotates in a bath of caustic solution at a temperature of 60 °C (140 °F), the operating temperature of the wiper is assumed to be that of the solution, and frictional heating is assumed to be minimal. The difference between the operating temperature and the glass transition temperature ΔT was determined. The L_{10} and L_{50} lives of the P-, A-, and R-series for an obverse printing job and the L_{10} and L_{50} lives of the P- and A-series material for a reverse printing job with respect to their associated ΔT are shown in Fig. 9. At the higher ΔT values, the operating temperature has advanced into the leathery or rubbery region, and thus the material is less prone to brittle and/or glass fatigue crack formation. The farther below the operating temperature the glass transition temperature has fallen, the longer the life of the material (Fig. 9).

The extent of crosslinking is another indication of material brittleness. As the number of crosslinks increases, the material becomes stiffer and more brittle and thus more prone to cracking. In the PVC materials (P- and A-series), the degree of crosslinking is indicated by the breadth of the tan δ peak (Fig. 4). The shorter-lived P-series material clearly had the broader peak with respect to the A-series material. Although the tendency to crack can be explained by these observations, the mode of crack initiations is still not understood and remains beyond the scope of this paper.
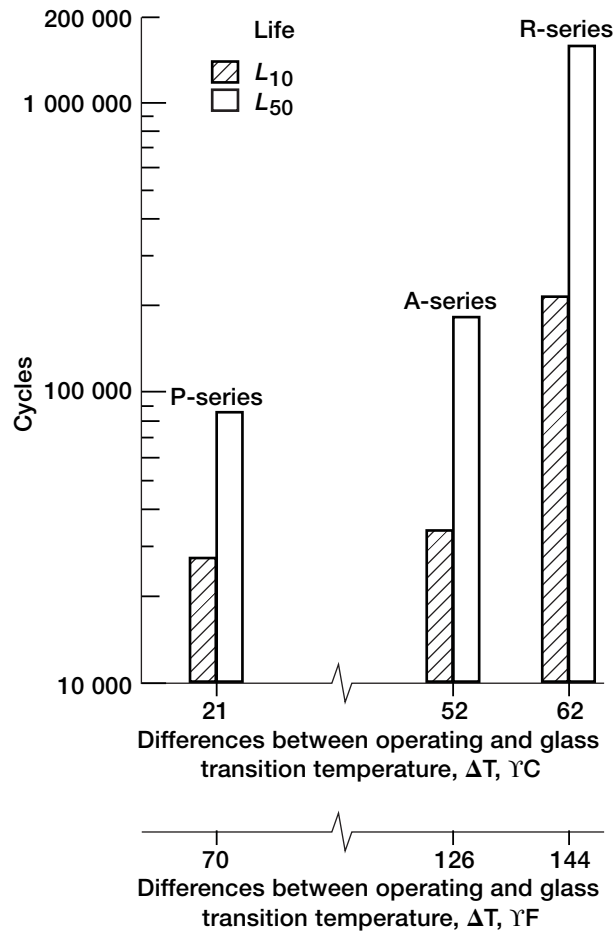
Figure 9.—L_{10} and L_{50} lives as function of operating temperature minus glass transition temperature ΔT for P-, A-, and R-series coating materials.

Cost-Benefit Analysis

In reference to Fig. 7 and Table 3, it is apparent that the coating that will produce the longest life and reliability is the R-series. However, if any of these coatings were to be used for aerospace or critical commercial applications where high reliability or low probability of failure is required, then the three-parameter Weibull analysis would become an important tool in ranking them. For a three-parameter analysis, the location parameter (the time below which no failure occurs) needs to be evaluated. Depending on the application, the location parameter and the cumulative distribution of the failures (Weibull slope) are important considerations in the selection of a coating. Here, the R-series coating gives approximately two and six times the lives of the P- and A-series, respectively. Again, on the basis of L_{μ} and comparing the P- and A-series only, the P-series exhibits a longer life by a factor of nearly 3.

For commercial noncritical applications where failure is benign (i.e., failure does not result in gross economic loss and/or in secondary damage or injury and death), the mean life or the mean time between removal (MTBR) can be considered a good measure of life. With reference to the mean life values for all three coatings for the two- and three-parameter Weibull analyses, the R-series coating exhibits

approximately 25 and 9.5 times the lives of the P- and A-series, respectively. When comparing the P- and A-series only, the A-series exhibits a mean life over twice that of the P-series. Making a coating selection based on mean life becomes rather easy. However, cost considerations also need to be factored into the selection.

For purposes of providing an example and for a cost analysis, it is assumed that the following costs and operating parameters are applicable to the use of the presses and coatings in a noncritical commercial application. The cost of the P- and A-series coatings are each $100.00. The cost of each R-series coating is $1200.00. The cost of replacing and installing each wiper coating is $100.00. The time it takes for replacing a coated wiper roller is 1 hr, which results in lost production valued at an additional $100.00. Excluding the cost and installation of the initial eight wiper coatings, the resultant cost of each wiper failure and replacement for P- and A-series coatings is $300.00 and for the R-series is $1400.00. It becomes obvious that it is more cost effective to replace the P-series coating with the A-series. However, it is not so obvious that the use of the R-series coating will be more cost effective than the use of the A-series coating.

A cost-benefit analysis was conducted using the foregoing scenario and a further assumption that the presses operate 8 hr per shift, three shifts per day, 6 days per week. It was assumed that individual presses make 8000 impressions an hour, which results in an individual coating receiving 8000 stress cycles per hour or 64 000 stress cycles in an 8-hr shift. Using the two-parameter Weibull analysis for each coating, the number of failures per each week was calculated for an entire year. The results for the first 2 weeks are shown in Table 5. The respective costs for each coating were calculated for 52 weeks of operation and are also summarized in Table 5. Both the cost and replacement rate for the R-series coating were significantly less than those for the P- and A-series coatings. The net cost of the R-series coating is approximately one-quarter and one-half the costs of the P- and A-series coatings, respectively. The total number of replacements for the R-series coating was 5 and 11 percent those of the P- and A-series, respectively.

TABLE 5.—COMPARISON OF REPLACEMENT RATE AND RESULTING COSTS OF RUBBER AND PVC WIPER CYLINDRICAL COATINGS IN EIGHT INTAGLIO PRINTING PRESSES

[Based on eight presses running three 8-hr shifts per day, 6 days per week using two-parameter Weibull analysis.]

Coating	Number replaced																First year total[a]	First year costs, dollars
	Week 1								Week 2									
	Day							Total	Day							Total		
	1	2	3	4	5	6	7		1	2	3	4	5	6	7			
P-series	13	17	18	16	18	19	--	101	17	20	17	17	16	17	--	104	5197 [b](5015)	1,559,100 [b](1,504,500)
A-series	4	7	9	9	8	9	--	46	9	8	9	8	7	7	--	48	2504 [b](1952)	751,200 [b](585,600)
R-series	--	1	1	--	1	--	--	3	1	--	--	2	1	--	--	[c]4	268 [b](213)	375,200 [b](298,200)

[a]Includes initial eight coatings in setup.

[b]Based on mean life from two-parameter Weibull analysis.

[c]Five replacements per week from third week on.

The number of replacements for each coating based on its respective MTBR was also calculated together with its respective costs. These values are also summarized in the parentheses in Table 5. Although the values calculated with each method are not exactly the same, they are qualitatively similar, and the same conclusions regarding cost and replacement can be reached.

It should be pointed out that in practice, the costs of the P- and A-series coatings are higher than those assumed and that the cost of the R-series is lower. Because actual productivity differed from that projected, the actual net cost differences between the coatings in actual use should be greater than those illustrated in the example given.

Summary of Results

Rotating, cylindrical, coated wiping rollers used in Intaglio printing fail primarily because of fatigue or misuse. In a production facility, three coating materials were evaluated on two printing presses dedicated to printing the obverse side of a product over a 9-month period. The standard coating used was a hard, cross-linked, plasticized PVC thermoset designated P-series. A candidate replacement coating was a plasticized polyvinyl chloride (PVC) designated A-series. The third candidate replacement coating was a commercially available hard nitrile rubber coating designated R-series. Sixteen P-series, one hundred and forty-two A-series, and eight R-series rotating, cylindrical, coated wiper rollers were evaluated on two frontface presses. Two- and three-parameter Weibull analyses and as a cost-benefit analysis were performed on the test results to determine the life differences and the cost related to the use of each coating. The following results were obtained:

1. The mean value of life for the R-series coating was 24 times longer than the P-series coating and 9 times longer than the A-series coatings. When a three-parameter analysis was used, the life of the R-series coating was approximately two times the life of the P-series coating and six times the life of the A-series before the first failure occurred.

2. The acquisition and operating costs using the R-series coating were approximately one-quarter and one-half the costs of the P- and A-series coatings, respectively. The total number of replacements for the R-series coating was 5 percent of those for the P-series coating and 11 percent of those for the A-series coating.

3. When all coatings were run to failure, using the mean (life) time between removal (MTBR) for each coating to calculate the number of replacements and costs provided results qualitatively similar to those using a Weibull analysis.

4. A relationship appears to exist between glass transition temperature and life: the farther below the operating temperature the glass transition temperature, the longer the life of the material.

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Three coating materials for rotating cylindrical-coated wiping rollers were fatigue tested in 2 Intaglio printing presses. The coatings were a hard, cross-linked, plasticized PVC thermoset (P-series); a plasticized PVC (A-series); and a hard, nitryl rubber (R-series). Both 2- and 3-parameter Weibull analyses as well as a cost-benefit analysis were performed. The mean value of life for the R-series coating is 24 and 9 times longer than the P- and A-series coatings, respectively. Both the cost and replacement rate for the R-series coating was significantly less than those for the P- and A-series coatings. At a very high probability of survival the R-series coating is approximately 2 and 6 times the lives of the P- and A-series, respectively, before the first failure occurs. Where all coatings are run to failure, using the mean (life) time between removal (MTBR) for each coating to calculate the number of replacements and costs provides qualitatively similar results to those using a Weibull analysis.

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