Nip Width of an On-Demand Fuser: Part I. Cross-section Model

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This article presents an experimentally verified analytical model of a pressure roller's nip when it is pressed against a flat heating element in an on-demand fuser. A cross-section model has been developed for predicting the nip width and deflection of a rigid pressure roller. In the mechanics literature, pressure rollers such as those used in laser printers are known as soft rollers. This model is based on nondimensional results from a finite element analysis that accounts for differences in roller size, rubber material, and load.

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Introduction

On-Demand Fusers. On-demand fusers are gaining popularity in laser printers because of their ability to adjust thermal power input rapidly during printing as well as their ability to conserve power when in a standby mode. In this type of fuser, paper moves between a flat heating element, protected by a movable sleeve, and a rubber coated pressure roller as illustrated in Fig. 1. A rubber-coated roller such as this is commonly referred to as a soft roller.

Nip Width and Deflection. An important variable in fuser performance is the nip formed between the pressure roller and the heater element. Pressure and temperature are elevated in the nip causing toner particles to melt and fuse to each other as well as the paper. The width of the nip controls the residence time available for this process. This report outlines a cross-section model for predicting nip width over a broad range of pressure roller sizes, rubber materials, and loads. The model assumes that the pressure roller is rigid, causing a uniform nip width along the length of the roller. A more elaborate model that accounts for bending of the pressure roller is described in Part II of this paper.[1]

The deflection of the pressure roller is another important variable. This is required in determining the load on the pressure roller when different weight papers are fed to the fuser. The cross-section model predicts this deflection as a function of pressure roller size, rubber material, and load. The deflection of the pressure roller calculated by this model is also essential in determining nip width variation due to roller bending.[1]

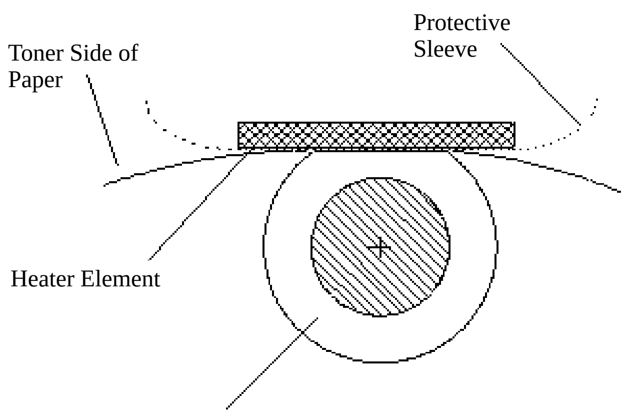

Figure 1. Schematic of a soft roller in an on-demand fuser.

Literature Review. A variety of results for soft rollers pressed against rigid rollers are found in the literature. Batra[2–4] applied finite element analysis to study soft roller response resulting from several different models of material behavior. Hahn and Levinson[5] present an analytical solution using an Aires stress function. Their solution can be extended to cross-sections with more than one layer of rubber, however the solution assumes that small strain theory is applicable. This drawback greatly reduces the solution's usefulness for soft rollers where maximum strains can reach 25%. Williams[6] describes a solution for nip width of xerographic pressure rollers. This solution, however, significantly underpredicts the nip width for on-demand fusers.

Pressure Roller Description

The solution method presented here is valid for a soft roller of any size with rubber of any modulus. In this study, two soft rollers were used to validate the finite element analysis. Soft roller No. 1 is a large scale model of a soft roller and was used to make nip width measurements. The large scale model allowed the nip width to be measured more precisely. Soft roller No. 2 is a pressure roller from a laser printer fuser and was used to make deflection mea-

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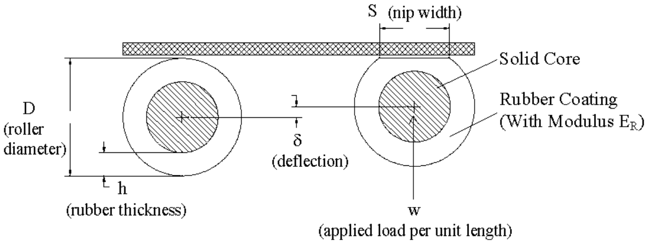

Figure 2. Variables used in cross-section model.

surements. The material properties of these two rollers are shown in Table I. The Young's modulus data was determined experimentally in an axial tension test.[7] Although the material response in terms of engineering stress versus engineering strain was nonlinear for these materials, the response was linear (up to 25% strain) after accounting for large strains. This was done by converting to true stress versus true strain before calculating the Young's modulus. The physical dimensions of the two soft rollers are shown in Table II.

TABLE I. Soft Roller Material Properties

Roller	Young's Modulus symbol	Young's Modulus psi	Poisson's Ratio symbol	Poisson's Ratio value
No. 1	E_R	700	ν_R	0.5
No. 2	E_R	85.5	ν_R	0.5

TABLE II. Soft Roller Dimensions

Roller	Roller Diameter (in)	Rubber Layer Thickness (in)	Roller Length (in)
No. 1	9.8	1.715	0.383
No. 2	0.625	0.116	8.69

Cross-Section Model

Variable Definition. The variables used to describe the cross-section of a soft roller are shown in Fig. 2. These are the diameter (D), rubber thickness (h), rubber modulus (E_R), load (w), deflection(δ), and nip width (S). The cross-section model can be simplified by applying a dimensional analysis. The dimensional analysis combines these parameters into four nondimensional groups. By doing this, nondimensional deflection (δ/D) and nondimensional nip width (S/D) become functions of only two nondimensional groups, nondimensional rubber thickness (h/D) and nondimensional load (w/DE). In this form, the nip width and deflection can be predicted over a broad range of pressure roller sizes, rubber materials, and loads.

Assumptions. This analysis assumes that the rubber coating of a soft roller is incompressible and linearly elastic.[7] This model does account for nonlinearity effect due to large strains in the elastomer. Although it may not be the case for all rubber materials, the elastomers used in this study were shown to be linearly elastic after accounting for large strains. Care should be taken that this is the case before applying this model. Most rubber materials have a Poisson's ratio of 0.5 and are therefore incompressible, as is assumed in this analysis. Because the rubber material is much more pliable than the core of a pressure roller, the solid core is assumed to be perfectly rigid.

In a two-dimensional stress analysis such as this, either a plane strain or plane stress assumption is made. At the center of the roller, the rubber layer is constrained from deflecting in the longitudinal direction (orthogonal to the cross-section). Only the two ends of the roller are in plane stress, where the rubber layer is not constrained and can deflect outward. Because a pressure roller in a laser printer is long, the majority of the roller is in the plane strain condition. Therefore, the plane strain assumption was made in the cross-section model.

This model assumes no friction or other shear forces exist in the contact region between the soft roller and heater element. The load applied between the soft roller and the heater element is assumed to be uniform along the length of the roller. This load may not be uniformly distributed if bending occurs in the roller.

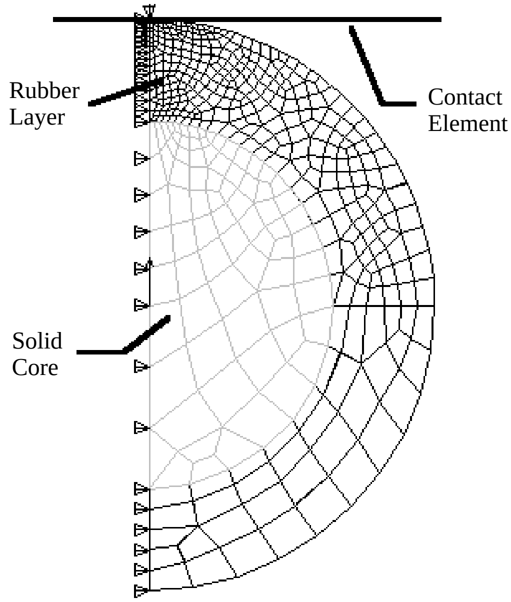

Figure 3. Use of contact element in finite element model.

Finite Element Analysis. The nip width and deflection of a soft roller under different conditions were determined by finite element analysis using the software package ANSYS (version 5.2). Both the solid core and rubber layer were modeled with quadrilateral elements. For the rubber layer, a large strain element was used that allowed strains up to 50%. The maximum strains in the rubber layer were calculated to be 25%, within the limit of this type of element. Figure 3 illustrates how a contact element was used to represent the flat heater element and prevent any rubber layer elements from moving above that surface. The load for the cross-section was applied at the center of the solid core, pushing the roller upward against the contact surface. Figure 4 shows the response of the soft roller in an uncompressed as well as a compressed state.

The deflection (δ) for each finite element case was the distance the solid core deflected upward. This is also the compression of the rubber layer and is analogous to the deflection of a spring separating the solid core from the contact surface. The nip width was found from the pressure distribution at the nodes touching the contact element. At the edges of the nip, the pressure decreases to zero. The edges were found by fitting the pressure data with a 7th order polynomial best fit curve and extrapolating that curve to a value of zero pressure. The distance between the two edges of the nip is the nip width. Extrapolating to estimate the nip width was necessary because the contact pressure is only calculated at node points.

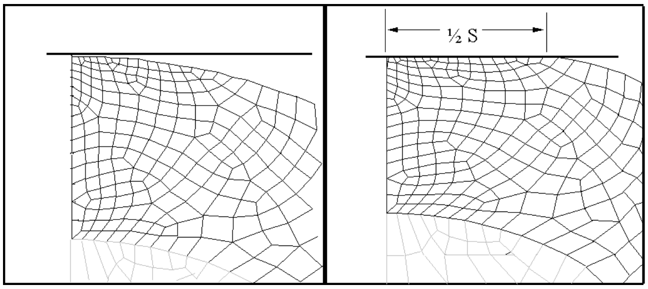

Figure 4. Finite element representation of soft roller in an uncompressed and compressed state.

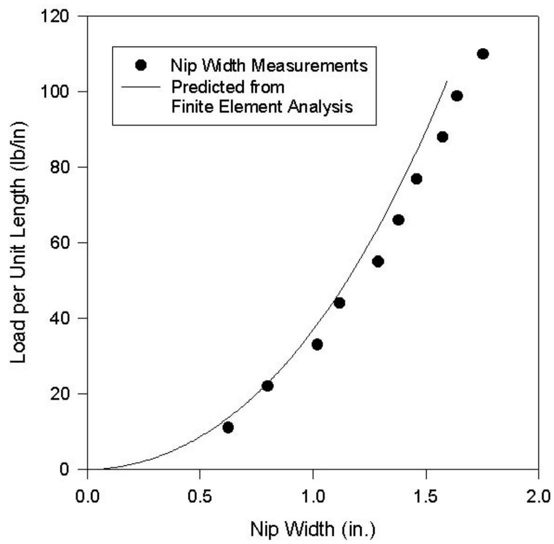

Figure 5. Nip width measurements with Roller No. 1.

In this analysis, combinations of seven rubber layer thicknesses and six loads were examined. This resulted in 42 different input conditions covering a broad range of roller sizes and loads. All cases have the same outer diameter (D = 0.625″), with an h/D ranging between 0.1 and 0.5. Six different loads were applied, with values ranging from 0.3 to 3.0 lb/in.

Model Verification

Nip Width Verification. Nip width predictions were verified using soft roller No. 1. Ink was placed on the bottom surface of this roller and then it was pressed against a paper strip. The nip width was measured from the width of the ink mark left behind on the paper. The uncertainty of these measurements is ±0.1 in. In Fig. 5, the nip width measurements are compared to the results from the finite element analysis. The agreement between the predicted and measured nip width is very good. The measured nip width is slightly higher than the predicted nip width at high loads.

Deflection Verification. A fixture was developed to measure the deflection of a soft roller. This fixture pinches a soft roller between two flat parallel surfaces. When tightened, the two parallel surfaces are brought together and pinch the roller. A micrometer was used to determine the separation of the parallel surfaces under a variety of loads accurately. The rubber layer on the top and the bottom of

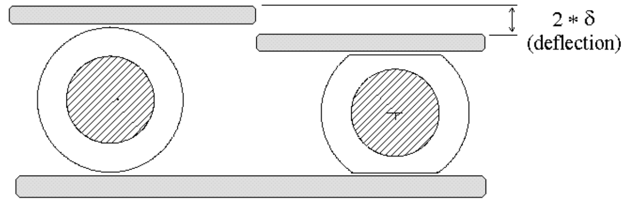

Figure 6. Fixture in an uncompressed and compressed state.

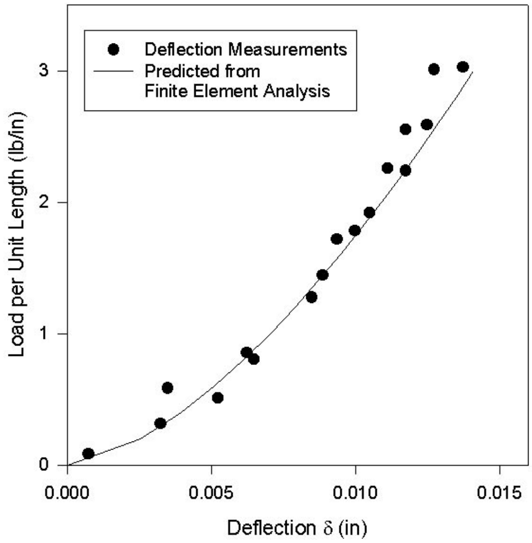

Figure 7. Deflection measurements with Roller No. 2.

the roller is compressed, as shown in Fig. 6. Therefore, the deflection measurement is twice what would be expected if only one side was compressed. Because of this, the deflection reading from the fixture is divided by 2.

The fixture was used to verify the cross-section model with roller No. 2. The deflection measurements for this roller are plotted against the finite element results in Fig. 7. The uncertainty of the deflection measurement is estimated to be ±0.001 in. The analytical and experimental results agree very well. They both predict a slightly nonlinear deflection versus force response of the soft roller, with the stiffness increasing with load.

Results

Nondimensional Nip Width. The nip width results, graphed in nondimensional form, are presented in Fig. 8. Each line on this graph represents a different value of nondimensional rubber thickness (h/D), ranging from 0.1 to 0.5. For each h/D value, the results are graphed with the nondimensional nip width (S/D) on the horizontal axis and the nondimensional load (w/DE_R) on the vertical axis. The graph shows that as the rubber layer thickness or the load increases, the nip width also increases. An increase in rubber layer thickness causes an increase in nip width because the rubber at the contact point can deflect more and distribute the load over a larger area.

These results show that the nip width behavior is highly nonlinear. This nonlinearity is often seen in contact problems, even in cases with small strains. The round elastic surface of the soft roller causes this nonlinear behavior. The nip width changes more slowly at higher values of w/DE_R and higher values of h/D. This indicates that the nip width is less sensitive to variations in rubber layer thickness at higher values of h/D.

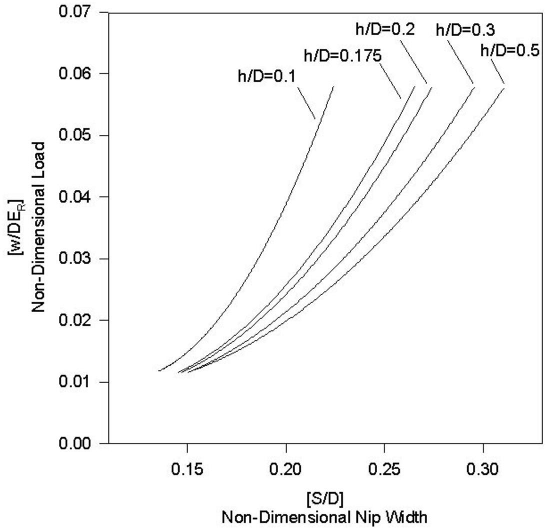

Figure 8. Nondimensional nip width as a function of load and rubber layer thickness.

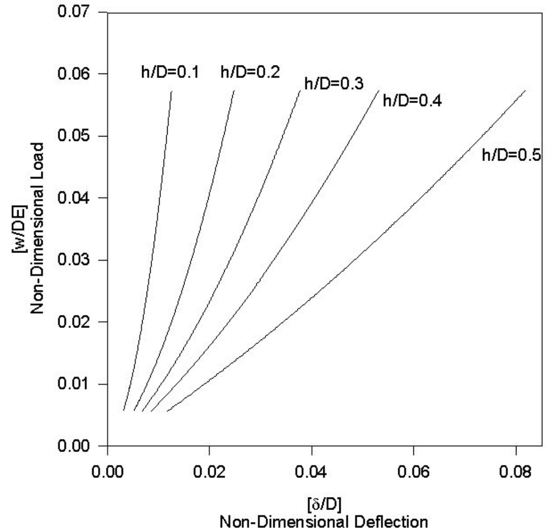

Figure 9. Nondimensional deflection as a function of load and rubber layer thickness.

$$\left(\frac{S}{D}\right) = \beta_0 + \beta_1\left(\frac{h}{D}\right) + \beta_2\left(\frac{w}{DE_R}\right) + \beta_3\left(\frac{h}{D}\right)^2 + \beta_4\left(\frac{w}{DE_R}\right)^2 + \beta_5\left(\frac{h}{D}\right)\left(\frac{w}{DE_R}\right). \quad (1)$$

The nondimensional nip width can be accurately expressed by Eq. 1 over a limited range. This range covers the operating conditions expected in an on-demand fuser. The range of this best fit function is $0.1 < h/D < 0.2$ and $0.01 < w/DE_R < 0.06$. The coefficients for this function are found in Table III.

TABLE III. Non-Dimensional Nip Width Coefficients

Coefficient	Value
β_0	$8.6763*10^{-2}$
β_1	$2.3851*10^{-1}$
β_2	2.7850
β_3	-1.1013
β_4	$-3.0867*10^{1}$
β_5	$1.1031*10^{1}$

Nondimensional Deflection. The deflection results, graphed in nondimensional form, are presented in Fig. 9. This graph is similar to the graph of a spring, with force plotted against deflection. Each line on this graph represents a different value of nondimensional rubber thickness (h/D), ranging from 0.1 to 0.5. The results are graphed with the nondimensional deflection (δ/D) on the horizontal axis and the nondimensional load (w/DE_R) on the vertical axis. The effect of the independent nondimensional groups can easily be seen on the graph. As the value of w/DE_R or h/D increases, the deflection steadily increases. The rubber coating thickness greatly influences the behavior of the deflection results. A soft roller with a thin rubber layer ($h/D = 0.1$) deflects much less than a roller with a thick rubber layer ($h/D = 0.5$) for a given applied load. This is because the strain accumulates over the thickness of the rubber coating and adds up to the total deflection. Therefore, under the same load, the deflection will increase as the nondimensional rubber thickness (h/D) is increased.

The deflection results are much more linear than the nip width results. The deflection behavior can be closely approximated by a linear function for a given nondimensional rubber thickness (h/D). This approximation is essential in developing a model for predicting nip width variation across a soft roller undergoing bending.[1]

Equation 2 represents a best fit of the nondimensional deflection over a limited range. This range covers the typical operating conditions expected in an on-demand fuser. The range of this best fit function is $0.1 < h/D < 0.2$ and $0.01 < w/DE_R < 0.06$. The coefficients for this function are found in Table IV.

$$\left(\frac{\delta}{D}\right) = \alpha_0\left(\frac{h}{D}\right)^{\alpha_1}\left(\frac{w}{DE_R}\right)^{\alpha_2}. \quad (2)$$

TABLE IV. Nondimensional Deflection Coefficients

Coefficient	Value
α_0	$6.49717 *10^{-1}$
α_1	$9.13428*10^{-1}$
α_2	$6.31418*10^{-1}$

Conclusion

A cross-section model has been developed for predicting nip width and deflection of a rigid pressure roller in an on-demand fuser. Finite element analysis of a soft roller in contact with a heater element has resulted in nondimensional correlations that can be applied to all sizes and speeds of laser printers. The model is applicable over the middle section of the pressure roller where the plane strain assumption is valid and the bending of the roller core is negligible. For detailed understanding about the variation in nip width due to roller bending, it is necessary to use the longitudinal model presented in the companion paper.[1]

The cross-section model can be used to make design modifications to obtain a specified nip width. This can be achieved by adjusting the load, roller diameter, rubber thickness, or rubber modulus. Insights about this interaction are suggested by the nondimensional groups that control nip width. For example, consider a pressure roller with fixed diameter and rubber thickness (i.e. constant h/D). For this roller, the nip width can be maintained constant by changing the load and the rubber modulus by the same percent.

The cross-section model can also be used to predict changes in nip width as a function of paper thickness. Typically, the heater element in an on-demand fuser is held against the pressure roller by a compression spring. Presence of paper between the heater element and the pressure roller will cause further compression of this spring . This will increase the load, thereby leading to an increase in nip width. For example, a sheet of 20-lb paper in a fuser with a compressed spring length of 0.7″ and a spring rate of 20-lb/in. would increase the nip width by 1% over the nip width when no paper was present. For a sheet of 50-lb paper, this increase would exceed 5%. These differences do not account for the presence of shear forces on the surface of the paper neglected in the cross-section model. Further research is necessary to quantify the effects of shear forces arising from paper friction.

Nip width is an important parameter in the thermodynamics of fusing. The nip width along with the paper speed determines the residence time for fusing. The cross-section model presented here could be elaborated to include irregularities in surface roughness and dynamic effects associated with paper friction. This is an important component in modeling toner adhesion.

Nomenclature

Symbol	Description	Units
Δ	= Roller cross-section diameter	in.
h	= Rubber coating thickness	in.
L	= Length of roller	in.
w	= Applied load per unit length on roller	lb/in.
S	= Nip width (width of contact patch between roller and surface)	in.
d	= Deflection of roller cross-section	in.
E_R	= Young's modulus of rubber layer	psi
ν_R	= Poisson's ratio of rubber layer	none
h/D	= Non-Dimensional rubber thickness	none
w/DE	= Non-Dimensional load	none
δ/D	= Non-Dimensional deflection	none
S/D	= Non-Dimensional nip width	none

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