Chapter 14.

Defining Sewability and Flexibility in Yarns

The idea of machine sewing an electrical trace element is highly appealing for many practical reasons. Machine sewing allows sewn electrical elements of almost any shape and size to be easily and quickly placed. Machine sewing allows continuous electrical traces to be sewn across the seams in a garment; this means that electrical continuity between two separate panels can be achieved. Machine embroidering electrical traces allows for the CAD control of the placement, size, texture and design of electrodes and other circuit elements. This chapter will define the necessary properties of machine sewable yarns and demonstrate a new *Curl Test* for judging the flexibility of yarns.

To make embroidered or machine sewn electrical elements requires using a thread that is machine

Summary of Characteristics of Machine Sewable Yarns

High tensile strength or tenacity. Tensile strength of ~580 to 1200 cN, or tenacity of 2.5 to 5.

Moderate % of elongation at breakpoint (between 12-30%).

Denier of under ~400.

Relatively smooth surface characteristics.

High flexibility, and resistance to shear and permanent deformation under bending. My *curl test* for flexibility will follow.

sewable, electrically conductive and maintains that conductivity under the mechanical stress of machine sewing. Over the course of this thesis, I have empirically observed that most conductive threads are NOT machine sewable. They simply cannot stand up to the compound mechanical stress of machine sewing through the needle. Conductive coatings can rarely withstand the forces of passing through the needle, and conductive fibers and yarns often jam the machine or simply break too easily.

One solution to this problem would be to create a new sewing machine. But this solution is flawed for two reasons. Practically, it is attractive to use the standard sewing equipment and facilities of the already huge and established textile industry. In addition, equipment that is used for sewing standard textile materials assumes that those materials have certain mechanical properties, including flexibility or the ability to resist permanent deformation under bending. These properties are not just suited to the machinery. They are ESSENTIAL to the appropriateness of a fiber or yarn for its use any textile that is intended for or human wear. Thus, the ability of a conductive fiber to be sewn or used in existing textile machines says a lot about how soft, durable, flexible and *wearable* it will ultimately be. This is not to say that non-sewable fibers cannot be incorporated into clothing. Certainly, there are fibers and methods that can incorporate these fibers into clothing. However, this does imply that the more flexible these fibers, the more suited towards use in clothing they will be. Currently, much work in smart textiles includes fibers that are appropriate for industrial purposes, and are not truly flexible. These might include glass fibers and polymers. Such fibers simply cannot withstand the mechanical stretching, flexing and bending, that clothing undergoes. Thus, the *Curl Test* for flexibility, which was created for this thesis, says a lot about the appropriateness of conducting fibers for any use clothing.

Background

The history of the mechanical and material analysis of textile fibers, yarns and fabrics is extensive and dates back at least to the early part of the 20th century.[1] (Yarns are composite materials spun from the raw materials of fibers, like cotton, wool or rayon. All threads are yarns. Fabrics are composite materials made from fibers or yarns.) The analysis of fibers and yarns, while using many of the same terminology and tests as standard engineering materials, has also developed some of its own terminology and tests, partially due to some of the unique and non-quantifiable properties of fibers and yarn. For instance, traditional stress/strain tests of both yarns and fibers are only partially useful due to the non-Hookian and anisotropic behavior of these materials.[2] Material measures unique to textiles include *tenacity*, a measure of the force required to break a yarn or individual fiber, which is measured in grams/denier and

[1] Goswami, Martindale, and Scardino, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).
[2] Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

denier a measure of the weight in grams of 9,000 meters of yarn.

While the study of the mechanical properties of fibers, textiles and yarns is extensive and detailed, there is no universal standard by which to describe the mechanical properties of yarns and threads in industry.[3] This may be a reflection of the fact that many yarns were used and developed long before they were described technically. In addition, textiles yarns are sold and spooled for a specific *function*, like machine sewing, warping, or knitting, and as a result many of the mechanical properties necessary for their *function* are simply ASSUMED when selecting the category of yarn. For instance, machine embroidery yarns are of higher tenacity, smoother finish, have less % of elongation at break and are spooled differently than woolen knitting yarns. They are also of a small enough denier that they can fit through the eye of a needle. Often these properties are not mentioned, but simply assumed in the term “machine embroidery yarn.” For this reason, it is important to remember when buying or examining an industrial yarn, that there may be no standard description of its mechanical properties beyond its *function*.

Standard descriptions of the properties of textile yarns may include:

[3] US Customs Service, *What Every Member of the Trade Community Should Know About: Fibers & Yarns, Construction and Classification under the Harmonize System An Advanced Level Informed Compliance, Publication of the U.S. Customs Service*, US Customs Website, http://www.customs.gov/imp-exp1/comply/fibryarn.htm#top, World Wide Web, (1996).

- Denier - the weight in grams of 9000 meters or Decitex weight in grams 10,000 meters[4].
- Strength may be described in the form of tenacity, (g/denier or cN/dtex), tensile strength (cN) or breakpoint (grams or newtons).[5]
- % of elongation at break, or elasticity and ductility.

When buying a conductive yarn it is difficult to determine whether or not it is appropriate for machine sewing, or for any fashion oriented textile use. Most conductive yarns are generally used for industrial purposes (like tire reinforcement or static control), and are usually not categorized, designed or labeled for specific textile functions, like machine sewing or knitting. Therefore, it is has not been possible to buy a conductive yarn that is labeled by the industry as machine sewable conductive yarn.

Introduction to Flexibility in Textile Materials

The standard mechanical properties that may be used to describe a yarn, its strength, denier, elasticity, and % of elongation at break, are by no means the only parameters necessary for successful machine sewing. Textile yarns, fibers and fabrics also possess the inherent property of *flexibility*. Much technical literature on yarns and fibers describes *flexibility* somewhat qualitatively as a property necessary and inherent to

[4] Ibid.
[5] Ibid.

fibers, yarns and textiles. The Textile Institute of New Jersey (1970's) defined fibers as "units of matter characterized by flexibility, fineness and a high ratio of length to thickness, (at least 1/1000)."[6] Qualitatively, *flexibility* can be understood as the resistance to permanent deformation under stresses like folding or bending. The importance of flexibility in any textile material or product simply cannot be overemphasized. A non-flexible fiber or yarn is simply not used in the textile industry.

While most textile fibers and materials are simply assumed to be flexible, many conductive fibers are not flexible. (Yarns are composite materials made from twisted or matted fibers.) The mechanical properties of yarns, including flexibility, are result of both the mechanical properties of the individual fibers from which they are made and the overall geometry of the yarn, which includes properties such as twist and continuous filament vs. spun or staple yarns, may be more important to the mechanical properties of yarns than the properties of the individual fibers themselves. As a result the flexibility of conductive fibers added to the yarn, as well as their geometry can affect the overall flexibility of the yarn. In addition, the amount of non-flexible fibers added to a yarn can directly effect the yarn's overall flexibility. Thus the flexibility of a yarn is related to the filler fiber's flexibility (its fineness or length vs. width, its flatness, young's modulus,[7]) the

[6] Goswami, Martindale, and Scardin, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).
[7] A more detailed description of flexibility is provided on page 235.

percentage of conductive fibers added to the yarn, and their geometry (for instance, continuous filament vs. non-continuous filament).

Machine Sewing

Machine sewing and embroidery, (essentially the same process), place enormous compound mechanical stresses on yarns. Machine sewing uses two threads, the top or needle thread, and the bottom or bobbin thread. The top thread must endure the mechanical stresses of tension, bending, shear and friction. The bottom endures far less stress.

1. **The top thread** must be able to endure compound mechanical stresses that include tension, bending shear and friction. The top thread must be able to withstand the tension of the pre-tensioning mechanism of the sewing machine, and the pull of the needle without breaking. This requires a yarn of relatively high tensile strength, high breakpoint, or high tenacity. The top thread must also withstand the lateral stress of bending and shear when it passes through the eye of a needle, is forced through fabric, looped around the bobbin mechanism and bobbin thread, and pulled tight to form a secure stitch. As a result, the top thread must be highly *flexible,* and able to change its shape, and bend from straight to looped quickly, and without permanent deformation. The top thread must also be relatively even and *dressed*; it have smooth surface characteristics, (there are few

standards for yarn dressings or coatings[8]), to reduce friction during the process of sewing. It must also be narrow enough to pass through the eye of the needle.

2. The bottom or bobbin thread is unwound from a bobbin spool. The top thread forms a loop around the bobbin thread to create a stitch. While the bobbin thread does not need to withstand the same bending stresses as the top thread, it is usually the same type of thread, or a thread with similar strength. There are many commercial threads or yarns that are designed and spooled for machine sewing in the bobbin. These yarns must to be of high tenacity (for textile yarns), relatively low denier, smooth surface finish and high flexibility.

General Characteristics of Machine Sewable Yarns

Consequently, machine sewable yarns must be of high tenacity, high flexibility, have a reasonable ductility or percent of elongation at break, be of small denier, and have a relatively smooth and even surface finish. The characteristics of machine sewable thread include:

[8] US Customs Service, *What Every Member of the Trade Community Should Know About: Fibers & Yarns, Construction and Classification under the Harmonize System An Advanced Level Informed Compliance, Publication of the U.S. Customs Service*, US Customs Website, http://www.customs.gov/imp-exp1/comply/fibryarn.htm#top, World Wide Web, (1996).

1. High tensile strength or tenacity. Tensile strength of ~580 to 1200 cN. Tenacity, 2.5 to 5.
2. Moderate % of elongation at breakpoint (between 12-30%).
3. Denier of under ~400.
4. Relatively smooth surface characteristics.
5. High flexibility, and resistance to shear and permanent deformation under bending. (My test for flexibility will follow.)

High Tensile Strength or Tenacity

Commercial embroidery yarns have a tensile strength of 580 - 1100cN. They have a tenacity that varies from 2.6 to 5. It is worth noting that *high tenacity* yarns are usually defined as industrial, not textile yarns[9]. Industrial yarns that are use in composite materials and tires may have tenacities as high as 7.2 to 8. Knowing the ultimate tensile strength or breakpoint of a yarn as opposed to just its tenacity may be important because a single ply of 2.5 tenacity yarn may not be machine sewable, while a double ply may be. It is important to note that doubling a yarn may impart additional tenacity or strength per denier to the yarn because twist adds to the strength of a yarn.

Moderate % of Elongation at Breakpoint

Machine sewable threads must resist both permanent lengthwise or ductile stretching, and elastic over-stretching under tension. Commercial embroidery threads have 12-30% elongation at breakpoint. An elastic yarn, (generally not machine sewable) might

[9] Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

have 100% or more elongation at breakpoint. In contrast, a 100% stainless steel yarn made from continuous untwisted filaments has 1% elongation at break. (Fiber geometry also plays a role here. This yarn is untwisted, which can increase separation of individual filaments and cause snags.) The role of individual fiber elongation in sewabiltiy is not straightforward, because both overall yarn geometry and fiber elongation can play a significant to role in the behavior of yarns. Individual cotton textile fibers, (which in many ways are the ideal raw material for machine sewing yarns), have a % of elongation at break point between 4-17 %. But cotton fibers are also extremely fine and make for very flexible yarns. Individual nylon filaments, have an % of elongation at break of between 15-40%. Nylon yarns are also made from continuous filaments and often have a yarn elongation of 30%. Thus, the non-sewability of nylon threads may be related to the ductility of fibers, but may also be related to the fact that is a continuous filament yarn. The elongation of individual stainless steel filaments is 30%. Ultimately, it is the yarn geometry of continuous untwisted filaments that gives yarns made from these fibers their low ductility.

Denier of ~Under 400

Commercial embroidery thread has a denier of ~ 120/2, that means 2 plies of 120 denier thread, for a total denier of 240. Standard upright sewing machines can use larger needles and therefore accommodate larger thread. The machine sewable BK50/2 has a total denier of 360.

Smooth Surface Finish

Relatively smooth surface finish and evenness. While a high degree of evenness and textile lubricant is ideal for machine sewable yarns, practical experience has shown that it is possible to machine sew with yarns with relatively poor surface characteristics. The most machine sewable conductive yarns in this research have both low evenness and no surface lubricant. The effect of a high amount of textile lubrication (like wax) on the conductivity of a sewn trace is potentially detrimental. The conductivity of sewn traces may rely on the surface contact of multiple non-continuous conductive fibers, both within an individual yarn, and between multiple conductive yarns that have been overstitched, or are used in both the bobbin and top thread. Observation has shown that multiple stitch paths and the use of conductive yarns in the bobbin and top threads have dramatically improved overall conductivity. Heavy textile lubricants and surface treatments can prevent electrical contact between layers of stitched yarns, and decrease the overall conductivity of a trace. However, the yarns in used in this work have been soaked in silicon for lubrication with no detrimental effects to conductivity.

High Flexibility

Yarns that permanently deform when bent are definitely *unsewable* in the needle of a sewing machine. I have created the *Curl Test* to test the flexibility of yarns, and their ability to be sewn in the needle of a commercial sewing machine. It is important to note that there is no industrial measure of flexibility in textiles. This is because, as previously stated, the flexibility of textile fibers, spun yarns, and fabrics is *assumed*. Moreover, there is little research into the mechanical definition of flexibility in textiles.[10] This may be because traditional textile fibers and yarns can be mechanically modeled as perfectly flexible, like the long cables of a suspension bridge. Consequently it can be argued that shear and bending forces simply disappear in relation to tension forces in textile fibers.[11] Qualitatively, the flexibility of yarns can be described as related to the fineness of its fibers, the yarn's twist and its denier.[12] One mathematical model (which will be looked at more closely later in this chapter) derives fiber flexibility from the formula for deflection in a cantilever beam. This model describes the flexibility of fibers and filaments as inversely proportional to the Young's modulus of the fibers and the diameter of the fiber cubed, and directly proportional to the length and flatness of the fiber.[13] Because the Young's modulus' of fibers is highly non-Hookian, this equation can only be used as proportional guide for *fiber* flexibility. Many conductive fibers or filaments are not *flexible*, and may make the yarns that use them unsewable. Overall yarn geometry can also contribute to flexibility.

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[10] Ibid.
[11] Ibid.
[12] Goswami, Martindale, and Scardin, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).
[13] Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).

Curl Test for Flexibility of Yarns

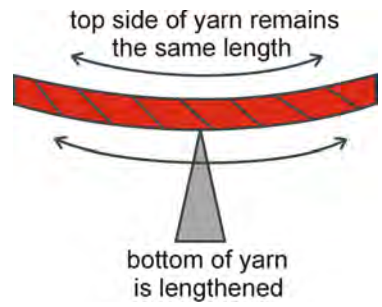
Because the flexibility (resistance to permanent deformation under bending) of yarns is related to both the flexibility of the fibers and their geometry in the yarn, traditional stress/strain curves may not describe the flexibility of every yarn. This is because, while non-flexible fibers may make a yarn inflexible, when that yarn is placed under lengthwise stress these fibers may simply slide past each other, giving no indication of how their addition affects permanent deformation when *laterally bent* (sewing is a lateral stress perpendicular to the length of the yarn).

To test the flexibility of yarns with non-flexible fibers, I have created a *Curl Test* for bending yarns and threads. This test is appropriate for judging whether the yarn is flexible enough for machine sewing through the needle. This test creates a bending stress similar to what happens when you curl a piece of ribbon. It is designed to lengthen and one side of a yarn. Because this test is a measure of the flexibility of a yarn, it is also appropriate for understanding it use as a textile material.

The test involvers 2 steps:

1) Bending or curling the yarn.
2) Reloading and straightening the yarn.

The final flexibility of an unsewable yarn is a reflection of:



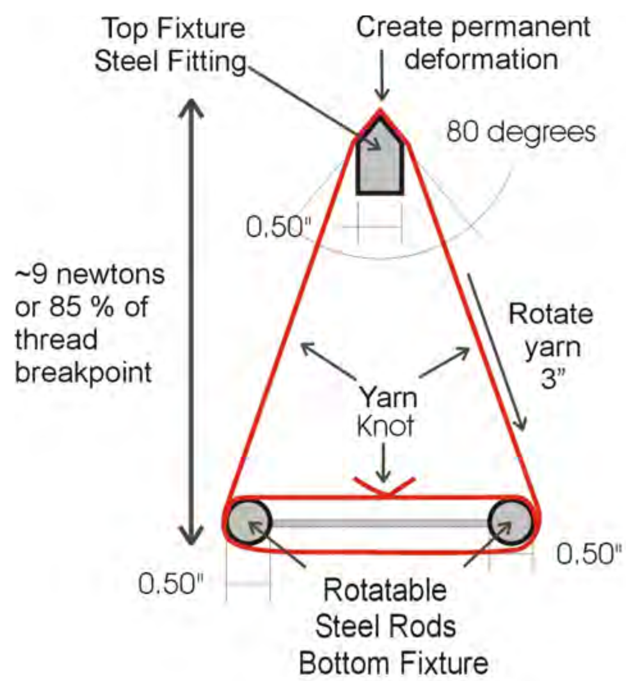


Figure 15.1, Yarn being curled, (above), and diagram of curl test, (below).

1) The diameter of curvature of the resulting curl. (> .0625")
2) The tightness of the curl, or the ratio of the diameter of curvature of the curl, to the length of the curl. The ratio must be above 1/3.
3) The number of curls created by this test. There must be at least three curls as described above.

1) Bending or Curling the Yarn

This step involves creating a loop of the yarn to be tested around a pair of fittings that are either independently attached to a materials loading system, or weighted. The top fixture is a metal point (similar to the blade of a scissors) that the yarn will run over. (The edge of this tool should be slightly broken so as not shear the yarn). The bottom fixture acts as a means for tensioning, looping, and then rotating the thread across this metal point. The yarn is tied in a loop around the top and bottom fixture. Once the fixtures are in place the thread is loaded to 85% of its breakpoint. (Different yarns will need to be loaded different amounts as a reflection of their tenacity or breakpoint.) This loading should make the yarn tight. (Machine sewable thread usually has a breakpoint of between 6-13n). I have found 9n to be a good load for many stainless steel threads. I have also found the breakpoint of some yarns to be less than what is given by the manufacturer, so a breakpoint test should be run on the yarn first. Once the yarn is looped around the top and bottom fitting, mark the yarn at the both first deformation point, and three inches away from it in the direction of the rotation. Once the yarn is loaded to

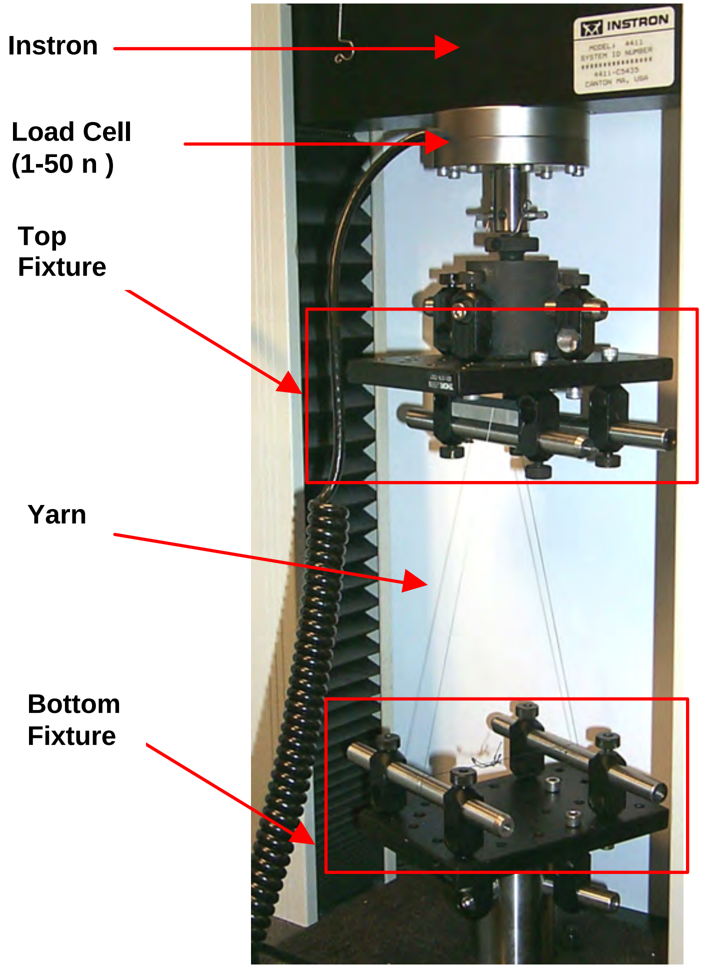


Figure 15.2 *Curl Test* on Instron materials measurement system.

85% of its breakpoint, it is then rotated around the fixture 3 inches. (This can be accomplished by turning the rods on the bottom fixture). The yarn is then cut, as far away from the top deformation point as possible.

At this point, a completely flexible yarn like rayon or cotton, will show no curl. Most yarns with non-flexible fibers will show some curling and twisting.

2) Reloading the Yarn

To truly judge if the yarn has been permanently deformed, the yarn must be reloaded. The fixture for reloading the yarn involves two rods with a 1/16" diameter hole drilled in the center. The yarn is threaded through the hole and the wound round each rod a minimum of three times.

If the yarn shows any curl at all after the curl test, it is then reloaded to 50-90% of the original load. (This varies for different yarns because the curl test can cause the yarn to yield and lower its breakpoint or tenacity.) This step involves loading the yarn to .5 of the original load and releasing it. If the curl remains identical, load to .6 of the original and so on, until 90% of the final load amount is reached. If the thread breaks before the final load amount, perform the curling test again and then reload the thread to the 10% less that the breaking point of the last sample.

Once the thread has been reloaded, it is ready for the final analysis.

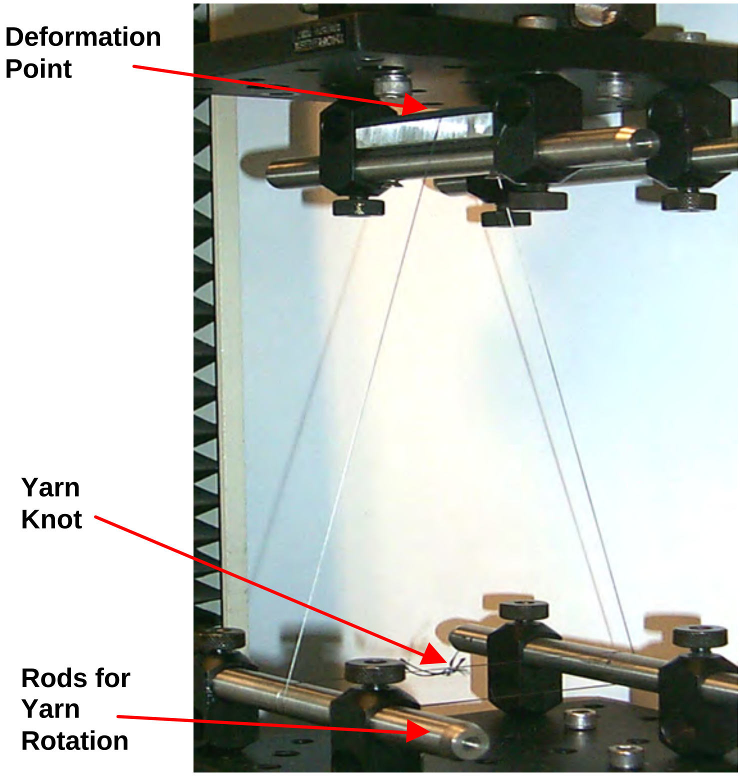


Figure 15.3 Close-up of *Curl Test* on Instron.

The Final Analysis

Three factors come into play in judging the flexibility of yarns after reloading.

1) The diameter of the curl of a yarn that is non-flexible as to be unsewable in the needle of a sewing machine is >.0625", (1/16)".

2) The ratio of the diameter of the curl to the length of the curl in the yarn must be between 1/3 and 1. In general, yarns with smaller ratios are more flexible. Yarns with a ratio of 1 are highly non-flexible. Yarns with a ratio of less than 1/3 or one 1/10 are flexible enough for sewing.

3) The curl caused by step one, must be repeated *at least three times*. A yarn with only one curl with a ration of ½ and a diameter > .0625" is still flexible enough for machine sewing in the needle.

Individual Yarn Results

Rayon Sewing Yarn (Machine Sewable)

No curling or deformation in Step 1.

BK 50/2 20% Non-continuous Stainless and 80% Polyester, (Machine Sewable)

In Step 1 this yarn was loaded to 7 newtons. Minimal curling occurred in step 1. The yarn was reloaded to 5 netwons. Curling was reduced to 3 curls with aspect ration well under 1/10 and diameter of under 1/16", and 1 curl with a larger aspect ratio and a diameter of ~.25". Therefore, the yarn is sewable.

70% Non-Continuous Stainless and 30% Kelvlar (Un-Sewable)

In Step 1, this yarn was loaded to 8 newtons. Substantial curling occurred. It was reloaded to 7 newtons. Curling was not reduced. There are 3 final curls, each with an aspect ration of .5. The final diameter of the curl is .25". It is not flexible enough for machine sewing in the needle.

100% Continuous Stainless Steel (Un-Sewable)

This yarn was loaded to 9 newtons and reloaded to 8 newtons, with significant curling occurring in Step 1 and no relaxation of curl in Step 2. There are 5 curls that result from the bending in Step 1. Their final aspect ration is close to 1 and the final diameter is between .125 and .25".

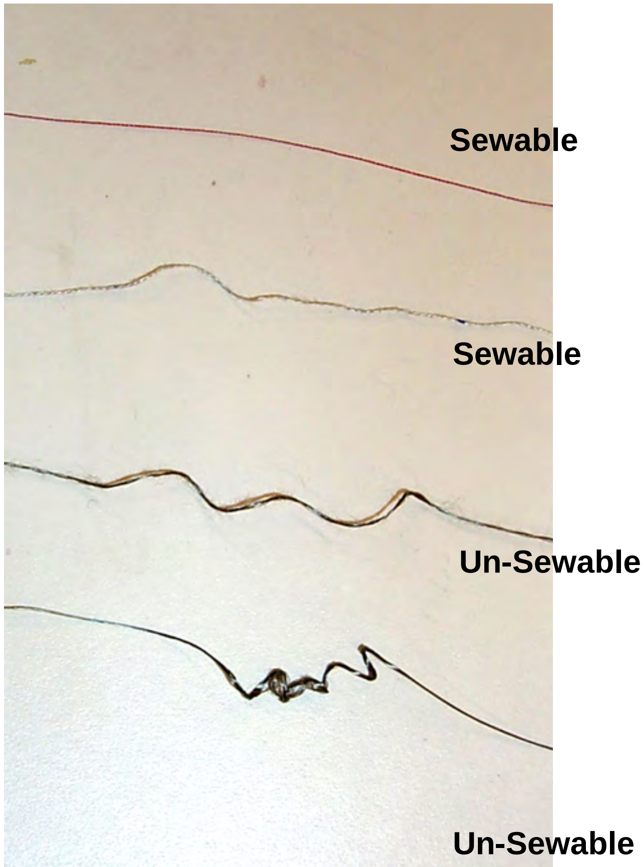


Figure 15.4 Yarns after Step 1 and Step 2 of the *Curl Test*.

More on Flexibility in Fibers

As stated previously, flexibility can be assumed as inherent to textile fibers, yarns, and fabrics. But while it is inherent, the technical exploration of flexibility is somewhat limited. In 1954, Kaswell stated that "…it is regrettable that little data are found in the literature on the topics of bending, torsion, and shear… It appears unnecessary to comment upon the importance of such deformations to fiber yarn or fabric performance." He also presented a mathematical model from earlier work done by Finlayson in 1946 regarding flexibility of fibers.[14] In 1977, the authors of Textile Yarns[15] choose to describe flexibility only qualitatively, stating that "the resistance to bending or flexibility of a fiber as depends on its shape, its tensile modulus, it density and above all its fineness (ratio or width to length)."

Finlayson's model of the inherent flexibility of textile fibers is significant for understanding the sewabilty of yarns made with conductive fibers. Finlayson makes an important comparison between flexibility in fibers and the standard physics of both the deflection of a cantilever beam under stress, and the bending modulus of a beam supported in the middle with deflected ends.

[14] Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).
[15] Goswami, Martindale, and Scardino, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).

Finlayson derives this equation for inherent filament and fiber flexibility from the equation for deflection in a cantilever beam loaded at the end. Please note that this equation has some unusual notation.

$$f = (\mathrm{f})\,\frac{Fl\,R^{3}}{EW^{4}}$$

where

f = deflection
l = length of cantilever
E = Young’s modulus of fiber (isotropic material)
F = applied load modulus
R=eccentricity of cross section, or major axis width/minor axis width
W = average diameter

According to Finlayson, this demonstrates that “the flexibility of a filament is directly proportional to its flatness, as measured by the ration of major to minor axis of the elliptical cross section, and is inversely proportional to its modulus of elasticity and the fourth power of its diameter.”

But while this equation can lead to a better understanding of flexibility in textile fibers, it does not provide a truly quantitative measure of this property in textile fibers. This is because textile fibers have anisotropic properties rendering their Young's modulus unspecific for this equation. Textile fibers show a high degree of non-linear and non-Hookeian deformation under stress. [16] However, it can be generally understood from this equation that the general stiffness, shape and above all the fineness of individual fibers contribute to their flexibility.

While this equation describes the flexibility of individual fibers, it is not necessarily relevant for yarns. Yarns are composite materials made from the twisting of fibers, that are held together by the forces between these fibers. As a yarn is tensioned, these fibers slide past each other allowing strain in the yarn to occur. This strain is non-Hookeian and anisotropic. The twist of most yarns imparts a far more complex geometric and mechanical relationship between fibers. While the documenting of these internal forces in twisted yarns is outside of the scope of this chapter, it is important to realize that the movement of fibers during the straining of a yarn may render the *stiffness* of the individual fibers irrelevant to overall fabric and yarn stiffness.[17] At the same time it can be said, that qualitatively, the *flexibility* of fibers, or fiber fineness, as well as twist play an important role in yarn flexibility[18]. The diameter

[16] Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).
[17] Kaswell, E., Textile Fibers, Yarns and Fabrics, New York, Reinhold Publishing, (1953).
[18] Goswami, Martindale, and Scardino, Textile Yarns, Technology Structure and Application, New York, Wiley-Interscience Publications, (1977).

or denier of the yarn also plays a role in the flexibility of yarn.

Flexibility in Conductive Fibers and Yarns

Unlike textile fibers, many conductive fibers have a clear Young's modulus. Consequently, Finlayson's equation for the flexibility of fibers can be essential to understanding the sewability of yarns made from conductive fibers. For instance, metal fibers in yarns may have a Young';s modulus anywhere for 80 GPa (Au) to 200 GPa (steel). In contrast, a spider's dragline has a modulus of 2.7-4.4 GPa and nylon a modulus of 3 GPa. The width and shape of non-textile fibers is also significant to its flexibility. In general, textile fiber widths can vary from 15 microns in fine cotton, to 50 microns for ramie. Wool fibers, which possess a width of 25 microns (which itself does not render them unsewable), a low tensile strength, and a circular cross-section is far less flexible than cotton and never used for machine sewing thread. Let' s compare wool with the drawn stainless steel fibers that are incorporated into yarns. Stainless steel fibers have a larger diameter of 35 microns, and a generally circular cross section. Thus, looking at the diameter, cross sectional shape, and Young;s modulus of stainless steel fibers may lead to the assumption that these fibers may simply be too inflexible to be incorporated into machine sewable yarns.

But it is important to remember that individual fibers are part of an overall yarn geometry. Thus, experiments with stainless steel yarns have shown that both yarn geometry, and the % of conductor incorporated into a yarn also play a significant role in a yarn's flexibility, and therefore its sewability.

Sewing with Conductive Yarns

The goal of the sewing process developed in this thesis was to machine sew a trace that was as electrically conductive as a wire. So why not just machine sew a copper wire, or even tack it into a piece of clothing? Aesthetically, one's initial reaction is that it is not soft or flexible enough to be incorporated into a textile. Mechanically, it is simply not machine sewable in either the bobbin or needle. There are compound reasons for this. A very thin wire will break under the tension of sewing in the needle or jam the machine in the bobbin. The machine sewable spun stainless steel and polyester yarn BK 50/2 has a diameter of .14 mm and a breakpoint of 1270 cN. Given a tensile strength of 400 GPa, a copper wire of similar diameter would have a break point of only 6N. A continuous stainless steel strand of .035 mm has a breakpoint of 91 grams. So a copper wire simply cannot withstand the tension of sewing in the needle. In the bobbin, it jams the machine. This is because it is not flexible. Given a wire of the same thickness and aspect ratio as a spun embroidery yarn it is safe to say that the Young's modulus of Cu, (124 GPa) is at least ten times higher than the Young's modulus of a spider drag line at 2.8-4.7 GPa.[19] I use a spider dragline for comparison because both are single filament continuous fibers and yarn geometry does not come into play when

[19] Rolf E. Hummel, Understanding Materials Science: History, Properties, Applications, Springer, New York, (1998).

understanding their flexibility. Because of their Young's modulus, copper wires that are simply tacked down, or couched into clothing, are also subject to extremely high bending forces. They cannot resist permanently deformation, and eventually will break.

The conductive yarns experimented with during the course of this research gained their electrical properties from either a metal foil wrapping, or the incorporation of stainless steel metal fibers drawn from stainless steel wire. We favored stainless steel because it provided a conductor that was resistant to corrosion, inert, known to be safe when worn next to the body, and affordable. One drawback to stainless steel was that it not as conductive as copper or gold. As previously noted, most of the yarns that contained metal fibers were not machine sewable. There are compound reasons for this, including the flexibility of the metal fibers used in the yarns, the ductility, or % of elongation at breakpoint of the yarn, and the overall yarn geometry.

The most successful machine sewing process developed to date uses a high resistance, highly flexible and soft staple thread of 20% stainless in the needle, combined with a highly conductive yarn of nylon wrapped with 3 filaments of continuous stainless steel in the bobbin. This process takes advantage of the lower mechanical stresses that are placed on the bobbin thread during sewing. It also relies on coupling a material with desirable mechanical properties and poor electrical properties (the spun stainless and polyester yarn which is highly flexible), with a material with poorer mechanical properties and great electrical properties (the yarn of nylon wrapped with continuous filaments of stainless steel.) It also relies on the layering and design of the stitch pattern. Certain stitch patterns create far more flexible and conductive electrodes. This process can create 4' electrodes with isotropic resistances of under 50 ohms. This remaining resistance is both a function of the conductivity of the yarns, and the fundamental conductivity of the cold worked steel.

Specific Yarn Analysis

Because each yarn's sewability is a compound property, (the result of its geometry, the flexibility and % of conductive fibers added), it is helpful to analyze each yarn used in this research specifically.

Metal wrapped Yarns or Gimped Yarns

Yarns wrapped in copper or gold foil, or *gimped* yarns, could not be sewn for two reasons. (Gimped yarns are yarns around which is wrapped another yarn or filament or strip.[20]) The internal yarn, or mechanical center the gimped yarns, was simply not of high enough tenacity to machine sew. Metal wrapped yarns like these are generally woven in the weft of a fabric (weft weaving creates little mechanical stress on a yarn), or attached to fabrics for decorative purposes,

[20] US Customs Service, *What Every Member of the Trade Community Should Know About: Fibers & Yarns*, *Construction and Classification under the Harmonize System* An Advanced Level Informed Compliance, Publication of the U.S. Customs Service, US Customs Website, http://www.customs.gov/imp-exp1/comply/fibryarn.htm#top, World Wide Web, (1996).

with a process called couching. Couching puts little stress on the thread because it involves mechanically attaching the metallic thread to a substrate material by *tacking it down* or sewing another thread around it. Neither of these processes require the threads to be of high tenacity. Of course, a gimped thread with a stronger central core could have been made. But this would not have addressed the delicacy of the metal wrapping or foil. The metal foil of the gimped yarns is simply not flexible. Under bending and lateral stress the metal foil was easily permanently deformed stripped, and broken, destroying the electrical continuity of the yarn. The metal foil would also jam the machine. The inflexibility of the metal foil was ultimately a function of its diameter and Youngs' modulus (copper 124 GPa and gold 82GPa). Yarn geometry also plays a significant role here. Gimped yarns are especially susceptible to the damage of the conductive wrappings because the foil is on the outside of the yarn, and is subject to a lot of stress and friction from the needle. It is worth noting that there are commercial embroidery threads available that are gimped with a metallized plastic coating. These coating are highly flexible due to both their diameter, and the Young's modulus of the plastic wrapping, which can be assumed to be very low. (Plastics can have Young's modulus as low as .003 GPa.) They also have smooth surface characteristics as a result of coating and lubrication.

Stainless Steel Yarns

The stainless steel yarns tested for machine sewabililiy are of four types.

1. A **staple yarn of polyester and short stainless steel fibers**. (A staple yarn is a yarn twisted from many short fibers) Various blends were tried, 20 % stainless and 80 % polyester was the only one conductive enough and sewable.
2. A **100% continuous filament stainless steel** thread, untwisted. This yarn was not machine sewable as a needle thread.
3. A **staple yarn of 30% Kevlar and 70% stainless steel**. This yarn was not machine sewable in the needle, but successful in the bobbin.
4. A **continuous filament yarn of twisted nylon and 3 continuous strands of stainless steel**. The yarn was not machine sewable in the needle, but machine sewable in the bobbin.

Staple or Spun Stainless Steel Yarns

Two types of staple, or spun, stainless steel yarns were used and it is worth comparing them. Highly resistive yarns of spun stainless steel and polyester fibers with a steel content of >20% (BK50/2)[21], and highly conductive yarns spun from Kevlar and stainless steel fibers with a content of 70% stainless steel[22].

BK50/2 stainless steel and polyester threads were successfully used in both the bobbin and top thread of a commercial embroidery machine. The main failure of these staple yarns of stainless and polyester was under tension. Single strand yarns were not of high enough tenacity to withstand the tension of machine sewing. A double stranded twisted that yarn withstood

[21] See Materials Index.
[22] Ibid.

sewing has a higher break point, both by virtue of its twist and increased denier. A double stranded yarn of 20% stainless steel has a tensile strength of 1270 cN, and a % of elongation of 15%. Single ply yarns had a strength of 580 cN (less than half of the double ply), and a percent of elongation of 12%. Yarns with stainless steel contents lower than 20% were not conductive enough for our purposes. It is worth noting, that increasing the content of the stainless steel also increased the yarn's tensile strength. Single ply yarns of 5% stainless steel have a tensile strength of 355 cN, while 20% stainless tensile strength of 580 cN (tenacity of 2.9 cN/dtex). Threads with 70% stainless and 30% Kevlar have a tenacity of 18.89 cN. While this high content stainless steel thread was sewable in the bobbin, it was not machine sewable in the needle. It permanently deformed when sewn.

Yarns with lower stainless steel content were more sewable. It is known that fibers in spun yarns move significantly when the yarns are under stress. Thus, while a single fiber of stainless steel might be bent or deformed during sewing, it would be free to move between the highly flexible fibers of the polyester. Therefore, while yarns of spun polyester and stainless with higher stainless steel contents than 20% are not manufactured, it is clear that adding stainless steel will make the yarns less flexible and less sewable.

Adding additional stainless steel fibers to the yarn would also increase short circuits between sewn traces. Staple stainless steel yarns have long stainless steel fibers that extend beyond the radius of the yarn. This is because the stainless fibers are inflexible and cannot be combed parallel before or during spinning. These fibers come loose in sewing and cause short circuits between traces. Small electrical connections in the 100's of mega ohms have been observed between adjacent sewn traces of 20% spun stainless steel. The 70 % content stainless steel yarns produced a higher the rate of short circuiting between traces, with short circuits as high as 100 ohms.

Yarns with Continuous Stainless Steel Filaments

This thesis looked at two categories of yarns made with continuous stainless steel fibers, a 100% stainless steel, a nylon wrapped with 3 continuous filaments and an untwisted yarn made of up to 200 strands of continuous stainless steel. The wrapped yarn was useable in the bobbin of the sewing machine. In the needle, the wrapping stripped. The continuous yarn made form bundled fibers was unsewable. It was simply too unflexible and did not have enough % of elongation at break.