CV of diameter, more specifically the former, in most cases had an adverse effect on carding performance and yarn properties. An increase in bulk resistance to compression had an adverse effect on yarn and fabric strength, fibre breakage during carding, fabric abrasion resistance and spinnability but had a beneficial effect on yarn extension, bulk and hairiness and on cross-card variation. An increase in mean fibre length, within the ranges covered, generally had a beneficial effect. A ‘length after carding’ test has also been developed in which a small scale card and double draft gill system are used to convert the scoured wool into a sliver suitable for Almeter fibre length measurement. It correlates well with actual results.

6.6 Spinning

6.6.1 Introduction

The ultimate aim of spinning is to produce yarn (i.e. a coherent and cohesive fibre strand) of the required linear density (count) and which has good evenness, tensile properties and a minimum number of faults.

Spinning can be divided into the following three basic operations:

i) Attenuation (drafting) of the roving, sliver (semi-worsted) or slubbing (woollen) to the required linear density.
ii) Imparting cohesion to the fibrous strand, usually by twist insertion.
iii) Winding the yarn onto an appropriate package.

Spinning machines can be divided into two main groups, namely intermittent (e.g. mule) and continuous (e.g. ring, flyer, cap, open-end, self-twist, twistless, wrap-spinning). It should be noted that wool is not commonly spun on the open-end (rotor) spinning system, although a recent paper indicates progress in this direction, 42 tex to 111 tex yarns being spun successfully from 20.5μm wool at speeds of around 100m/min. Nevertheless, the wool has to meet very strict requirements in terms of residual grease levels (0.1 to 0.3%) and fibre length; for example, an average fibre length of 30 to 40mm is required for a 46mm rotor diameter, with the longest 1% of fibres not exceeding about 60mm.

6.6.2 Ring spinning

Because of its versatility in terms of yarn linear density and fibre type, and also the superior quality and character of the yarn it produces, ring spinning (Fig. 6.10) remains by far the most popular system for spinning wool, particularly for fine yarns, there being some 16 million long-staple ring spindles installed worldwide. It includes two-strand and compact/condensed type spinning.
The input into the ring-frame can be twistless (rubbed) or twisted (flyer) rovings in the case of the worsted and semi-worsted system, slivers in the case of the semi-worsted system, and slubbings in the case of the woollen system. Double apron drafting, draft typically 20, is generally used in modern ring-frames, except in low-draft woollen spinning and some of the high-draft spinning systems.

The yarn production of ring-frames is limited largely because of limitations in the speed of the traveller on the ring (around 40 m/s maximum), due to excessive wear and heat being generated by the traveller at high speeds, as well as by the yarn tension and tension variability (peaks) generated during spinning. The maximum spindle speed is normally around 13000 r/min and yarn production 40 m/min. The tension on the yarn can be controlled by the traveller, largely depending upon the frictional resist-
ance of the traveller against the ring, which in turn is largely determined by
the rotational speed. Requirements of the traveller include good heat dis-
sipation, sufficient thread space, matching of traveller size and shape to the
ring flange and good sliding properties.¹

Yarn spinning tension is affected by the length and diameter of
the balloon, the use of balloon control or suppression devices (e.g. rings,
and spindle attachments) enabling the yarn tensions in the balloon to be
reduced by reducing (semi-collapsing) or collapsing the balloon, thereby
allowing spinning speeds and/or package sizes to be increased and power
consumption to be reduced. Traveller speeds as high as 45 m/s become pos-
sible when, for example, using sintered rings and nylon travellers. The use
of collapsed balloons is particularly important for the larger packages used
in woollen and semi-worsted spinning systems.

Rotating rings were explored as another way to overcome traveller
speed and yarn tension limitations, but they have not yet found wide
application.

According to Oxtoby¹, about 85% of the total power requirements of a
ring-frame is consumed in driving the spindles (depending on yarn density,
package size, spindle speed, etc.), the balance being consumed by the draft-
ing and lifter mechanisms.

The following factors have the main influence on spinning conditions:¹

- Ring diameter (affects package size, yarn tension, traveller and spindle
  speeds, power consumption, capital costs, floorspace and doffing costs).
- Balloon height (affects power consumption, capital cost, floorspace,
  doffing costs, balloon collapse). Longest balloon height without balloon
  collapse is the most economical.
- Spindle speed.
- Traveller mass.

Spinning production and cost are related to the level of twist inserted, which
in turn is related to spinning efficiency (end breakage rate) and yarn prop-
terties (notably tensile, bulk, hairiness and stiffness). The minimum twist
required to produce acceptable spinning performance and yarn properties
is normally selected.

It is generally held that surface fibres have the same angle of inclination
to the yarn axis when yarns have the same twist factor (turns/cm \(\sqrt{\text{tex}}\)), and
that such yarns therefore have a similar geometry. Fibre migration (vari-
able helix angle at different positions along the fibre length) determines the
yarn structure, and properties and can be characterised by:¹

- Mean fibre radial position
- Migration amplitude
- Mean migration intensity (i.e. rate of change of radial position)
Modern ring frames can incorporate automatic doffing, sliver/roving stop motions, thread break indicators, electronic speed and package building programs, and automatic piecening, data collection, ring cleaning. They can also be linked to the winders, with a cop steamer stage between spinning and winding.\textsuperscript{52}

Turpie\textsuperscript{53} developed the MSS accelerated spinnability test while Huang \textit{et al.}\textsuperscript{54,55} developed a model for predicting end breaks in worsted spinning. Yarn strength variation, followed by mean yarn strength and spinning tension were the main factors in the model. They found that the spinning tension varied considerably, the CV being typically 15 to 20\%. End breaks are caused either by the yarn spinning tension exceeding the yarn strength (more particularly that of the yarn weak places) or by flaws, such as neps, vegetable matter and short fibres, in the input material.

Various studies,\textsuperscript{26,56} have shown that mean fibre diameter is by far the most important fibre property in terms of spinning performance and limits, and yarn quality, this largely because of its effect on the number of fibres in the yarn cross-section when yarn linear density is constant. It is followed in importance by mean fibre length (a 10 mm change in mean fibre length having approximately the same effect as a 1 \( \mu m \) change in mean fibre diameter), then fibre length distribution (CV and short fibres), fibre crimp (lower crimp generally beneficial), fibre strength and CV of diameter (a 5\% absolute change in CV having approximately the same effect as a 1 \( \mu m \) change in mean fibre diameter).

For worsted ring spinning, spinning limits are normally taken to be 35 fibres in the yarn cross-section although commercial spinning limits range between 40 and 50 fibres, generally 50 for dyed fibres. Normally, around 40 to 50 end breaks per 1000 spindle hours represent the maximum acceptable limit for commercial spinning of wool.

The average number of fibres (n) in the yarn cross-section can be calculated as follows:

\[
\text{n} = \frac{972 \times \text{yarn linear density}}{D^2 \left[ 1 + \left( \frac{\text{CV}_D}{100} \right)^2 \right]}
\]  \hspace{1cm} \text{[6.13]}

where

\begin{align*}
\text{yarn linear density} & \quad \text{is in tex units,} \\
D & \quad \text{mean fibre diameter (\( \mu m \)),} \\
\text{and CV}_D & \quad \text{CV of fibre diameter (\%)}
\end{align*}

For a fairly typical CV\textsubscript{D} of 24.5\%, equation [6.13] becomes:

\[
\text{n} = 917 \text{tex}/D^2.
\]
According to Martindale, the limiting (or ideal) yarn irregularity (CV_L) assuming completely random distribution of fibres, can be calculated as follows:

\[
CV_L(\%) = 100\sqrt{\frac{1 + 4\left(\frac{CV_D}{100}\right)^2}{n}} [6.14]
\]

which becomes

\[
CV_L = 3.208D\sqrt{\frac{1 + 5\left(\frac{CV_D}{100}\right)^2}{\text{tex}}} [6.15]
\]

or

\[
CV_L = \frac{3.208\text{Fe}}{\sqrt{\text{tex}}} [6.16]
\]

where Fe is the effective fineness as termed by Anderson.

Fe illustrates the relative effects of D and CV_D on yarn irregularity as well as on yarn and fabric stiffness.

An irregularity index (I) for yarns and slivers is also often used to provide a measure of the yarn unevenness relative to the fibre used.

I can be calculated as follows:

\[
I = \frac{CV(\%)}{CV_L} [6.18]
\]

If CV_D = 25% this becomes:

\[
I = \frac{CV(\%)}{\sqrt{n}} \frac{\sqrt{112}}{112} [6.19]
\]

where CV(%) = actual or measured yarn or sliver irregularity and n = the number of fibres in the yarn (or sliver) cross-section, calculated according to eq. [6.13].

I = 1.2 is regarded as very even for worsted yarns and 1.4 for fine woollen yarns.

Bona gave the following empirical relationship, based upon an important worsted spinning mill in Biella, which enables the optimum fibre fineness (diameter) to be calculated if the desired yarn linear density is known,
and the optimum yarn linear density to be calculated for a given fibre fineness or diameter:

\[ \bar{n}_s = \frac{150}{\sqrt[3]{Nm}} = 15(\sqrt[3]{\text{tex}}) = 15(\text{tex})^{0.33} \]  

where \( \bar{n}_s \) = optimum average number of fibres in the yarn cross-section.

Comprehensive empirical studies have been carried out at the CSIR in South Africa\(^2\) and the CSIRO in Australia to relate ring spinning performance and yarn properties to top fibre properties and to derive empirical relationships that quantify the various effects and enable prediction. The following are examples\(^2\) of the empirical relationships derived in South Africa on the bases of the results obtained on more than 1000 wool worsted yarns.

\[ \text{Irregularity (CV\%)} \propto D^{0.8}L^{-0.2}\text{Compr.}^{0.1}\tex^{-0.4} \]  

\[ \text{Tenacity (cN/tex)} \propto D^{-0.8}L^{0.4}\text{Compr.}^{-0.2}\tex^{0.2} \]  

where

- \( D \) = Mean fibre diameter (\( \mu \)m)
- \( \text{Compr.} \) = Resistance to compression (mm)
- \( L \) = Mean fibre length (mm)

The general empirical relationship between Irregularity and number of fibres (\( n \)) in the yarn cross-section and mean fibre length (\( L \)) was found to be:

\[ \text{Irregularity (CV\%)} \propto L^{-0.2}n^{-0.4} \]  

The CSIRO work has led to the Sirolan Yarnspec prediction software,\(^6\) which has been superseded by the Topspin computer program that combines top prediction from greasy wool and prediction of spinning performance and singles worsted yarn properties, also including commercial costing details. It also enables the spinning mill to benchmark itself against ‘best commercial practice’.

According to the work of Gore \textit{et al.},\(^6\) the fibre tensile properties do not significantly affect processing performance, from re-combing to yarn and fabric, until the fibre extension at break falls below about 28 to 32\% (corresponding to a bundle tenacity of 7 to 9 cN/tex), after which a significant deterioration in performance may be found. Nevertheless, some work\(^6\) indicates that a 10\% change in fibre bundle strength has approximately the same effect on spinning end breaks as a 6 to 9 mm change in Hauteur.

Cheng \textit{et al.},\(^6\) applied Neural Networks to successfully predict spinning performance and yarn quality.
6.6.3 Two-strand spinning (Twin-spun)

Considerable efforts have been directed towards eliminating two-folding (plying) in the production of weaving yarns, the ultimate aim being to produce as fine a yarn as possible on the spinning frame, which can be woven without resorting to either two-plying or sizing. In the main, two approaches have been followed, namely: Two-strand spinning (e.g. Sirospun and Duospun) and Compact (condensed) spinning.

Two-strand spinning, also referred to as spin-twist or double-rove spinning, involves two rovings being fed separately to the same double apron drafting system, each strand receiving some twist before they are combined at the convergence point after the front rollers. Two examples are Sirospun (Fig. 6.11) and Duospun, the former using a mechanical break-out device and the latter suction and automatic repiecening to prevent spinning when one strand breaks. It is also possible to include a filament (flat, stretch or textured). In the case of Sirospun, the only modifications required to the ringframe are the following:

6.11 Two strand (Sirospun) spinning. [From Plate.]

---

**Diagram Notes:**
- Spinning system
- Drafting system
- Spacing guides
- Break-out device
- Spindle

---
• New rear roving guide to feed the two rovings separately to the rear rollers
• Central roving guide, fitted behind the aprons, which controls the strand-spacing
• A front zone condenser with two condensing slots at the correct strand spacing
• Break-out device
• Provision for double creels

The strand length (thread length between the convergence point and the nip of the front rollers) should be a minimum, it being related to the strand spacing. The strand spacing needs to be optimal, as large strand spacing beneficially affects yarn hairiness and abrasion resistance but adversely affects spinning performance. Spinning limits are about 35 fibres per strand cross-section, a low short fibre content being important. A minimum of 0.8% lubricant prior to combing is required, and 4 drawing passages are desirable. A draft of 20 appears optimum. Sirospun reduces spinning costs by some 55% on average but increases weaving costs by about 1% because of slightly higher yarn breakage rates.

Maximum yarn strength occurs at a tex twist factor of between 38 and 41, increasing to about 44 for very fine yarns. The recommended tex twist factor for a Sirospun yarn is around 38 ($\alpha = 120$). Typically, the tenacity of the two-strand yarn is equal to, or slightly greater than, that of the corresponding two-ply yarn, its extension 10 to 30% greater, its irregularity slightly greater, its hairiness slightly less and it contains more thin places. It also produces a more streaky fabric. Its abrasion resistance falls between that of two-ply yarn and that of a singles yarn of similar tex and twist. Compared to a two-ply yarn, however, it is twist-lively (similar to a singles yarn). It is also more circular and less easily deformed. Yarn joint quality is very important, splicing (thermal and pneumatic) generally being preferred, particularly for medium and coarse yarns. Z/Z Fisherman’s knots also give good performance, particularly for fine yarns.

Approximately 2% of a suitable lubricant (e.g. anionic) in the final rinse of the package dyeing cycle reduces yarn-to-metal friction and improves warping and weaving efficiencies. The application of a suitable lubricant during beaming also improves weavability.

Double-rove spinning of woollen slubbings (lambswool) on a woollen ringframe has also met with some success.
6.6.4 Compact (condensed) and related spinning systems

6.6.4.1 Compact (condensed) spinning

Following upon the two-strand spinning developments, further work has been undertaken to produce ring-spun singles yarns with superior properties (notably tensile, hairiness, abrasion and pilling). The ultimate aim was to be able to weave the yarn without plying or sizing. Considerable success has been achieved, although it is not yet possible to produce, in one operation, ring-spun wool yarn with the same weaving performance as the traditional two-ply yarn. It has been stated, however,\textsuperscript{70} that such yarns are not necessarily a direct substitute for the traditional yarns but that the fabric structure may have to be adapted to the new yarns.

A number of papers\textsuperscript{70–74} at the 2000 International Wool Textile Research Conference in Aachen dealt with Compact and related spinning techniques.

The width of the spinning triangle (fibre beard) has been shown to be related to the spinning tension as well as to the hairiness and imperfect integration of the fibres into the yarn.\textsuperscript{75} Considerable effort has therefore been directed towards narrowing (condensing) the spinning triangle at the exit of the front rollers. Most of the resulting systems, also referred to as condensed spinning, involve a condensed, narrow spinning triangle at the front roller nip (Fig. 6.12),\textsuperscript{76} and better control of the fibres at the exit of the front roller nip and their integration (binding) into the yarn, eliminating peripheral fibres. This has been done by introducing an intermediate (condensing) zone between the front roller delivery and the yarn formation (twist insertion) point, in which the fibrous ribbon width and spinning triangle are reduced, giving improved spinning efficiencies, fibre alignment, smoothness, hairiness, tensile properties and compactness in the yarn, as well as less fibre waste. The condensing systems used to accomplish this, and which are generally easily attached to, and dismantled from, the spinning frame, generally involve pneumatics (vacuum), applied, for example to a perforated front roller, lattice or apron.

Examples include the EliTe spinning system of Suessen, ComforSpun (Com4) of Rieter, and Air-Com-Tex of Zinser.

6.6.4.2 Solospun\textsuperscript{73,74}

Solospun (developed by WRONZ, CSIRO and IWS) merely entails the clipping of a pair of grooved plastic rollers to the drafting arms of the spinning frame, in front of the delivery rollers. These split the fibre ribbon emerging from the front rollers, and do not permit twist to reach the front roller nip, allowing the fibres (substrands) to twist and recombine in such a way as to increase the localized twist (cohesion) and compactness of the
substrands and yarn, as well as the fibre integration into the yarn. Thermo-
splicing (hot air) is recommended, the average splice strength should be
80% that of the yarn. Relatively even yarns of 25 tex to 50 tex and tex twist
factors from 33 to 43 (at least 38 for weaving yarns) can be spun, and coarser
fibres utilised (65 fibres in yarn cross-section), longer fibres being prefer-
able. Compared to two-fold yarns, yarn production costs can be reduced by
up to 50%.

6.6.5 Bicomponent spinning

Bicomponent yarns, also referred to as bound yarn, have found a niche
in the market, these generally combining pre-spun continuous filament
yarns with staple fibres to provide improved properties, such as stretch (e.g.
\textit{Lycra}) and strength. Bicomponent spinning\textsuperscript{77} (see Fig. 6.13)\textsuperscript{66} normally
involves twisting together either a filament (sometimes water-soluble) or
pre-spun staple yarn and a conventionally drafted staple (wool) strand
during the spinning operation. It is particularly attractive for the cost-
effective production of superior yarns, which can, for example, be woven or
knitted without any further operations (i.e. eliminating plying, sizing and
steaming). It also enables coarser fibres to be spun into finer yarns, reduces spinning end breakages, allows higher winding speeds and enables yarn and fabric properties to be engineered by suitable selection of the two components and the way in which they are combined. On the negative side, bicomponent yarns are generally not pure wool or torque-balanced and produce fabrics that are generally more streaky and air permeable and have more conspicuous joints. A suitable type of ‘break-out device’ can be used to prevent the production of a single component yarn. Steam setting at 80 to 85 °C is recommended (55 to 60 °C if a water-soluble filament is used).

6.6.6 Self-twist spinning

On the Repco self-twist spinning machines (Fig. 6.14), S and Z twist is inserted alternately into each of a pair of strands, which are then brought together, out of phase, along their length to wrap around each other, thereby forming an alternating twist two-ply structure (22 cm total cycle length) in which the torque of the two strands is balanced by the folding torque of the pair. The drafting zone is a modified double-apron system (back rollers, aprons and front rollers), optimum draft being around 25 for wool. Twistless or lightly twisted (maximum twist in turns/metre $= 644 \text{tex}^{-0.5}$) rovings can be used.
When the pair of strands leave the drafting zone, they pass between a pair of synthetic rubber covered rollers which cooperatively rotate and axially oscillate in opposition. The self-twist yarn that is produced is wound directly onto cheeses (yarn tension in cN = 0.3 \times \text{tex}). This system circumvents the limitations associated with package rotation and balloon formation that apply in ring spinning. The self-twist is dependent upon the tension applied to the yarn. Such self-twist wool yarns can withstand tensions of up to 60 mN/tex but need to be up-twisted for weaving, giving what is termed twisted self-twist (STT) yarn.

Some useful definitions and concepts follow:

**Self-Twist-Factor (STF)** = Average self-twist per half cycle (t/m) \times \sqrt{\text{tex}}

Generally STF = 1550

**Pairing Twist Factor (PTF)** = \frac{\text{pairing twist (t/m)}}{\text{STF on average}} = 1.55 \times \text{STF}

For twisted self-twist (STT) yarn the up-twist factor or added twist factor (ATF) may be calculated as follows:

\[ \text{ATF} = \text{PTF} + 880 \]

The above twist factors can be converted to tex twist factor (i.e. t/cm x \sqrt{\text{tex}}) by dividing them by 100.

In addition to the original self-twist (ST) yarn, a number of other versions of self-twist yarns exist, including the use of one filament (STm) or two filaments (STm)m, as well as their up-twisted and plied versions.
Although self-twist spinning has many advantages over ring spinning, such as production rate, floor space, waste levels, cleanliness, spinning limits (35 fibres per strand), noise levels, power consumption, it is not used much today for spinning wool, but rather for spinning high bulk acrylic for knitting.

6.6.7 Wrap (hollow spindle) spinning

Hollow spindle wrap-spinning (Fig. 6.15) shown at the 1975 Milan ITMA, in which continuous filament yarn, on a hollow spindle, is wrapped around...
an untwisted wool core (the latter accounting for typically 80 to 95% of the yarn composition), has also found some application for wool.

In plain yarns, the number of wraps required per unit length is generally very similar to the number of turns (twists) per unit length used for the equivalent ring-spun yarns. The economics tend to favour wrap-spinning for yarns coarser than about 50 tex. Such yarn is not twist lively and has a soft handle, the yarn being more suitable for coarse count knitting than for weaving. Wrap-spun yarns tend to be less hairy and bulky and equal to, or better, in strength and evenness, and can be spun finer than the ring yarn equivalent. Spinning limits generally lie between about 30 and 60 fibres in the yarn cross-section. The fine filament wrapper is expensive, however.

Nunes et al.\textsuperscript{80} established empirical equations relating wool core/nylon wrapper yarn properties to the yarn structural parameters, separating the effects of the staple fibre from those of the filament wrapper. Naik and Galvan\textsuperscript{81} also empirically related wrap yarn properties to spinning machine variables. Xie et al.\textsuperscript{82} showed that the strength of a wrap yarn was largely due to lateral pressure generated in the staple core by the binder helix. Choi\textsuperscript{83} also presented a yarn model that accurately predicted how wrapping pitch affected the yarn load – extension properties. In a study on woollen wrap-spun yarns, Cheung and Cheng\textsuperscript{84} found that wrapped yarn elongation was higher than that of ring yarn, increasing with wrapping density and also with yarn linear density, being higher without than with a false twister.

6.6.8 Other spinning systems

6.6.8.1 Treotek

Treotek is a WRONZ developed variation of the Sirofil, adding two filaments, which can be water soluble (or one filament plus a pre-spun yarn), to staple wool fibres. The number of wool fibres in the yarn cross-section can be as low as 20 (or even 15).

6.6.8.2 Cerifil

The Cerifil (Bigagli) system replaces the traditional ring and traveller with an inverted funnel-(cone)-shaped winder, resembling a cap, which is rotated by the yarn itself. It performs two basic functions, namely retarding the winding of the yarn and acting as a rotary balloon limiter, reducing yarn tension (which is adjustable) and end-breakage rate. The Cerifil system, which also eliminates the balloon break, can be incorporated into both semi-worsted and woollen ring frames.
6.6.8.3 Plyfil

The Plyfil (Suessen) system (Fig. 6.16), first unveiled at the 1987 ITMA, consists of a five-roller, two pairs of apron drafting system, with drafts of up to 400, being fed by slivers. The Plyfil machine has been referred to as a ‘spin assembly winder’. Yarns are consolidated by a sheath of helically wound fibre ends, wrapped around the fibre core in one direction by air-spinning jets behind the drafting system. The two twistless yarns produced on the Plyfil machine are wound onto each cross-wound package, assembly wound fashion. Generally, two-for-one twisting follows, the folding twist being in the opposite direction to the wrapped fibre sheath but lower than that for conventional two-ply yarn. It can also be used for the worsted spinning of wool, preferably using combed sliver.

6.7 Twisting

The twisting operation, also referred to as plying or folding, is the process where two (sometimes more) yarns are twisted to form a two-ply (or multi-ply) yarn. Traditionally this was done on a ring-frame (ring-twister) but today it is almost exclusively carried out on a two-for-one twisting machine (Fig. 6.17), three-for-one twisting systems having also been developed. Assembly winding is used to assemble two ends of yarn on one package in preparation for two-for-one twisting. It is particularly important to ensure that the two yarns are wound at the same tension. The assembly wound package remains stationary, the yarn passing through a guide mounted on a rotating arm which can freely rotate, through the hollow rotating spindle,