STUDIES OF QUALITY IN COTTON: WHAT HAVE WE LEARNED SINCE BALLS, 1928?

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Abstract

The book, "Studies in Quality in Cotton," was published by W. Lawrence Balls in 1928 as a summary of a ten-year research project carried out first in Egypt and then at the Rothamsted Experimental Station and Lancaster in England. The initial project mission was the translation of cotton-spinning technology into terms that would enable cotton breeders and growers to provide cotton with those qualities that improved processing success. Later, Balls added the objective of constructing a fiber property-based "Prediction Formula" by which the cotton grower could anticipate the results of a spinning test. This review compares the methodology and results summarized by Balls in 1928 with data obtained through modern fiber-quality measurement techniques. Like the 1928 report of Balls, the current review places particular emphasis on those results that provide predictive insights into the relationships between fiber properties and yarn strength.

During the past seventy years, Balls' reports published between 1915 and 1928 have been cited frequently by both fiber physiologists and textile technologists. Such bibliographic citations have usually been included as historical background for modern studies made wi
versatile or powerful than the light microscopes, mechanical balances, and prototypic fiber sorters available to Balls. However, despite such limitations in analytical capabilities, Balls established that there is a close relationship between fiber fineness [by weight] and yarn strength, or as Balls said, "the weaker the hair, the stronger the yarn." He inferred that increased fiber fineness resulted in more fibers being present in the yarn cross-section and that the presence of more, although finer fibers, increased yarn strength. He also related the frequency of fiber convolutions and degree of fiber surface 'slipperiness' to fiber strength as a function of 'draftability' and the distribution along the length of the yarn of the fiber 'weak links' related to convolutions. The 'strength' or thickness of the fiber secondary cell wall was also seen as an important component in fiber and, therefore, yarn strength. Fiber length, despite being the most easily measured fiber property, was thought to be least important in deciding yarn strength.

Early in the project, Balls determined that the *single* cotton fiber should be taken as the unit in which all spinning problems had to be described and solved. Having realized that producers, chemists, and spinners regarded cotton fiber quite differently, he advocated a multi-disciplinary approach to fiber quality, an approach in which 'cotton fiber' would be considered as discrete hairs, rather than as bulk lint yield, contaminated cellulose to be purified, or bales of homogeneous raw material to be processed. Recognizing the marked and inherent variability in cotton fiber, Balls noted that "no two hairs in a thousand are reasonably similar" even when examined at the level of resolution provided by the comparatively crude instruments available to him.

The high degree of variation among cotton fibers and the 'graders' judgment' of the hand classers and the instrumentation limitations of his day led Balls to predict that there was "no likelihood that any elaborate systems of hair testing can ever supersede the grader's rapid handling." However, he felt that development of a quick, precise measurement of fiber fineness by weight was possible [and highly desirable] after he had designed a prototypic 'sledge' fiber sorter.

By 1918, Balls had *quantified* the significant variations in fiber length within classers' standards of bulk cotton. He attributed some of this variability to individual 'classer bias' but recognized that there must also be marked variation in fiber properties within the sample. The 1918 standard-sample length distributions in Egyptian-grown cotton were not unlike the variability in fiber length by weight distributions found within and between individual locules of 'PD3' cotton grown in 1992 in South Carolina.

In establishing his relationships between yarn strength and fiber properties, Balls followed thirteen distinct fiber samples from Upland cotton genotypes through to spun yarn. Using light-microscope techniques that required minimal sample fixation, he found marked inter-sample differences in fiber 'ribbon width' [diameter]. Modern instrumentation such as AFIS, which allows rapid quantitation of fiber diameter by number, shows that variation in Upland fiber diameter at the locule level can have the same range as the ribbon-width variations Balls found among his thirteen fiber-to-yarn samples.

Without access to modern statistical analyses, Balls used graphical comparisons to determine which fiber characteristics might be related to the yarn strengths of his thirteen samples. When his data were arranged in ascending order of sample yarn strength, only the 'intrinsic' fiber strength which included a fiber weight factor approximated the trend of yarn strength across the thirteen samples. Balls inferred that fiber wall thickness should be closely related to fiber weight, and he explained the lack of correlation among wall thickness, fiber weight, and yarn strength by the presence of confounding artifacts in his light-microscope measurements of ribbon width, wall-thickness and cross-sectional area. Fiber-to-fiber variability was recognized as an additional confounding factor since it was practicable to measure only "the ribbon and wall in at least a hundred hairs, preferably . . . near the middle of each hair."

Considering the degree of variation present in fiber length, Balls warned that his microscopic examinations of such small lots of fibers were mostly likely biased with respect to sample selection and subject to significant experimental error. In his studies, the cross-sectional area was calculated from the width of the fiber lumen and the ribbon width with an estimated range of fiber cross-sections from 450 to 130 square micrometers for the coarsest [Burmese Wagyi] and finest [Sea Island] genotypes available at the time. The fiber-to-fiber variation in cross-sectional area ranged from 50 to 500 square micrometers, and Balls attributed the variation fiber life history, *i.e.*, the growth environment. In the 1992 fiber samples, the mean cross-sectional areas of 'PD3' fibers from fruiting positions one and two and branches seven through eighteen varied from 40 to 130 square micrometers with a mean and standard deviation of 105.4 ± 18.7 square micrometers.

By 1928, microscopy and analytical chemistry had advanced sufficiently for Balls to identify five chemically distinct layers in the fiber cross-section, *i.e.*, the exterior 'wax' layer, primary wall 'cellulose', secondary wall cellulose laid down in 'diurnal rings', and the remains of the lumen protoplasm. The diurnal rings were visualized by swelling fiber cross-sections in cuprous ammonium hydroxide, but available chemical analytical and microscopic techniques were not powerful enough to allow characterization of the changes in structural and/or chemical composition that were visible as 30 or more distinct rings in the swollen fibers.

Modern chemical analyses have shown the outer wax layer encrusting fiber cells to be composed of a complex mixture of esters of fatty acids and long-chain alcohols, free long-chain fatty acids and hydroxy fatty acids, free long-chain alcohols [primary, secondary, and diols], long-chain alkanes, and long-chain ketones. The principle component of the fiber cuticle is cutin, a complex mixture of hydroxy fatty acids linked together by ester bonds to form a three-dimensional network. The majority of the fatty acids in cutin contain sixteen or eighteen carbon atoms and may be saturated, monounsaturated or multi-hydroxylated. Balls recognized that the 'cellulose' of the primary wall differed from the cellulose of the secondary wall, but he did not have the necessary analytical capability to separate and identify the polysaccharide and pectic components of the primary wall. From his light-microscope studies, Balls inferred chemical bonds between primary and secondary components and the presence of secondary wall 'building blocks' or 'micelles' that appeared to contain microfibrils that were beyond the optical resolution available to him.

Over the seventy years that followed the publication of Balls' book in 1928, a great deal has been learned about the crystalline structure of the cellulose that is the major component of the fiber secondary wall, but there is still much to be learned about the synthesis of cellulose and the role of cell-wall proteins in that synthesis. However, the 'dilution effect' observed during fiber maturation as the proportion of the fiber weight attributed to the calcium-rich pectins of the primary wall is diluted by the synthesis of secondary wall cellulose has been used as the basis of a fiber maturity test that quantifies calcium weight ratios by x-ray fluorescence. Also, new instrumental techniques have allowed carbohydrate chemists to monitor fiber wall synthesis by quantitative and qualitative studies of types and polymerization rates of the ~mers being added to the cellulose of the secondary wall during fiber maturation.

In 1928, Balls acknowledged the limitations of fiber quality measurements available to him when he said " . . . [when] further research has demonstrated the existence of connections between hair shape and the density of the yarn . . . it will be necessary to take the microscopic measurements more seriously." Limited as he was to light microscopy and mechanical balances, Balls could not have anticipated the invention of rapid, reproducible fiber-quality measurement technologies such as the AFIS particle sizer that now allows statistical comparisons of the degree of fiber wall thickening [theta] with yarn breaking strength. For example, theta and, therefore, yarn strength clearly depended on growth environment in four Upland cotton genotypes grown in South Carolina in 1991 and 1992. As theta, fiber maturity, and micronaire increased, yarn strength in grams per tex also increased in a linear manner. As Balls predicted, increases in fiber cross-sectional area were associated with decreasing fiber strength.

The accuracy and continuing validity of Balls' inferences concerning fiber and yarn properties and their interrelationships are quite astonishing. How did Balls infer so much about fiber and yarn quality without access to the modern instrumentation that *still* does not always supply a complete description of those relationships? A portion of his success clearly comes from his recognition that the variability of cotton fiber, both inherent and introduced during and after harvest, demands that fiber-quality studies include replicated examinations of as many samples as labor and time permits. Further, Balls drew on measurement technology from a wide range of disciplines. If no instrument existed for quantifying a fundamental fiber property, he borrowed and adapted technology developed for sizing wire, determining the inside diameters of glass tubes, or measuring the stomatal apertures on plant leaves. When sorting fibers by length became an essential technique for his research, he developed his own 'sorter' that produced fiber arrays sorted according to length.

Working as he did toward the end of the era of the great 'natural [observational] scientists', Balls devoted an entire chapter in his 1928 book to the "Researcher's Code" that can be summarized by the three R's of modern scientific research: **Replicated** [so that each determination is repeated and every sample is replicated]; **Representative** [so that quantitative descriptions of a population are presented as means with standard errors and qualitative results show *only* examples of the 'average' form of the phenomenon being reported]; and **Reproducible** [so that the phenomenon can be shown to recur when the experimental conditions are reproduced.]

By closely adhering to his own researcher's code, Balls laid out the basics of fiber quality and the rudiments of the quantitative relationships between fiber properties and yarn processing results. Modern investigators of the connections between fiber properties and spinning and dye-uptake success should consider carefully some of Balls' findings concerning relative fiber wall thickness. "[Relative wall thickness] is of importance to cotton-spinning since it largely determines the fineness of the cotton." "Within a group of . . . a hundred hairs from the same seed . . . the wall thickness [varies] four- or five-fold."

Although Balls never considered fiber maturity as a distinct fiber property and found no connections between yarn strength and those fiber properties now recognized as maturity-related, his exacting and replicated microscopic examinations of fibers and yarn allowed him to make several still-valid statements regarding motes, neps, and fiber maturity. "Secondary wall formation can fail . . . so that the ripe hair consists of only primary wall." "Hairs such as these, . . . with those which have little secondary thickening, are industrially important because the primary cellulose reacts differently to dyes . . . " "These [immature] hairs are so flexible that they roll up easily into the knots and tangles called 'neps' in the mill . . . Nep does not exist in the living boll . . . " but can be introduced by rough fiber handling and particularly by the carding process.

Balls also recognized that the hand-harvesting of his fiber samples introduced a bias toward better fiber quality. Anticipating the mechanization of cotton production, he expressed concern about the negative effects on fiber quality of mechanical harvesters that could not differentiate between 'good' bolls containing high-quality fiber and diseased or damaged 'bad' bolls from the weathered late-season regrowth 'second picking' assigned 'mattress-stuffing grade' by modern producers. Indeed, Balls defined and anticipated most of the fiber-quality 'problems' that are still under investigation seventy years later. By insisting on the scientific rigor and quantitation that were becoming the bases of the physical and biological sciences of his day, Balls established the rules for *scientific* investigations cotton fiber and yarn properties and established a standard for conducting fiber-quality research that those who cite Balls' publications today would do well to apply to their own studies of cotton.

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