Textile Research Journal Article

Measurement Precision and Evaluation of the Diameter Profiles of Single Wool Fibers

Abstract A recent model of the Single Fiber Analyzer 3001 (SIFAN3001) was firstly employed to obtain the single wool fiber diameter profiles (S_fFDPs) at multiple orientations. The results showed that using SIFAN3001 to measure fiber diameter at four orientations for 50 single fibers randomly sub-sampled from each mid-side sample can produce average fiber diameter profiles (AS_fFDPs) of fibers within staples. Within the testing regime used, the precision estimates for the total samples were ±1.3 μm for the mean fiber diameter of staples and 1.4 μm for the average fiber diameter of the AS_fFDPs at each scanned step in the diameter profile. The mean diameter ratio (ellipticity) obtained from the four orientations was 1.08±0.01, confirming that the Merino wool fibers under review were elliptical rather than circular. The elliptical morphology of wool fibers and the precision of the fiber diameter measurement at each point along a fiber will be considered in the development of a mechanical model of Staple Strength testing.

Key words wool, ellipticity of wool, fiber diameter profile, precision, SIFAN3001

H. Wang and T. Mahar
Research and Development Division, Australian Wool Testing Authority Ltd, Sydney, NSW 2161, Australia

X. Liu and X. Wang[1]
Centre for Material and Fibre Innovation, GTP building, Deakin University, Geelong, VIC 3217, Australia

Wool fiber diameter and length are the most important properties used to determine the processing route and ultimate quality of the processed wool textile products [1]. The variance of fiber diameter further affects the processing performance [2,3]. Fiber diameter profiles are used to describe the diameter changes along and across a staple and the locations of minimum and maximum diameter within the staple. Accordingly, the knowledge of single diameter profiles (S_fFDPs) is critical to the development of a mechanical model of Staple Strength (SS) [4]. Extensive investigations into fiber diameter profiles along a staple (StFDPs) have been conducted in relation to farm management, SS, and processing performance [5–10]. However, the single fiber diameter profiles have not been thoroughly investigated in terms of their connection with the properties of a fiber staple.

Different technologies are available to measure the fiber diameter profiles or part thereof [6,11,12]. The Optical Fiber Diameter Analyzer 2000 (OFDA2000, BSC Electronics Pty Ltd., WA) has been used for testing StFDPs and is available for on-farm testing [12,13], whereas the testing reported by Hansford has been used for research purposes [7]. A limitation of these techniques is that fiber diameter is measured at one random orientation, and that it is not possible to trace the diameter profile of an individual fiber within the staple. In contrast, the Single Fiber Analyzer (SIFAN, BSC Electronics Pty Ltd., WA) can measure S_fFDPs under a small pre-tension force and can provide

[1] Corresponding author: tel: +0061 3 5227 2894; fax: +0061 3 5227 2539; e-mail: xwang@deakin.edu.au

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the tensile properties of single fibers [6]. In particular, the recent model SIFAN3001 is capable of measuring the S_fFDPs along a single fiber at different orientations by simultaneously rotating the upper and low clamps; hence the fiber ellipticity can also be evaluated along the fiber length.

The work reported in this paper is part of an investigation into the relationship between S_fDFPs and StFDPs. A SIFAN3001 instrument (one of two instruments currently available) was firstly employed to test the S_fFDPs at multiple orientations for single wool fibers which were sub-sampled from mid-sides of sheep. That is, the combined average single fiber profiles (AS_fFDPs) from the testing at four orientations were carefully examined for mid-side samples of three Merino flocks from different regions in Australia. Furthermore, the precision of the measurements within the testing regime was estimated for mean fiber diameter (MFD) of the samples and average fiber diameter of the AS_fFDP at each scanned step. In addition, the ellipticity (or circularity) of wool fibers was evaluated using the data from the measurements at four orientations.

Experimental

Fiber Preparation

Mid-side samples were taken from three flocks (Flock H, Flock B, and Flock T) which were run in major wool growing regions of Australia. Flocks B and T were run in the New England and in central areas of New South Wales, respectively, and Flock H in Western Australia. A small number of sheep that produced staples of typical SS (40.1 N/ktex for Flock B, 25.8 N/ktex for Flock H, and 21.6 N/ktex for Flock T) were selected from each flock (seven sheep from Flock H, six from Flock B, and three from Flock T) and one greasy staple was selected from the mid-side sample of each sheep. The greasy staples were first cleaned by a mixture of alcohol and a non-ionic detergent (Teric) and then conditioned in a standard atmosphere of 20 ± 2°C temperatures and 65% ± 3% relative humidity. Then, 50 single fibers were randomly sub-sampled from the base of each staple and prepared for fiber testing.

The sub-sampled single fibers were prepared one by one on A4-sized transparent films as shown in Figure 1. The fixed length of the base end was 10 mm. Each fiber specimen was manually de-crimped and the full fiber length was measured manually. The distance (*D*) between the fixed base and tip was calculated as the staple length minus 20 mm. To simplify sample preparation and the setup of SIFAN3001, the same *D* was used for all fibers from a staple.

Once ten fibers were fixed on a film, the fixed fiber tip and base ends were each covered by a layer of adhesive tape. Before mounting a fiber onto SIFAN3001, the film and sticky tape fixing tip, or base ends on both sides of the film were cut into a square shape approximately 8 mm long in order to facilitate their mounting into the clamps of SIFAN3001.

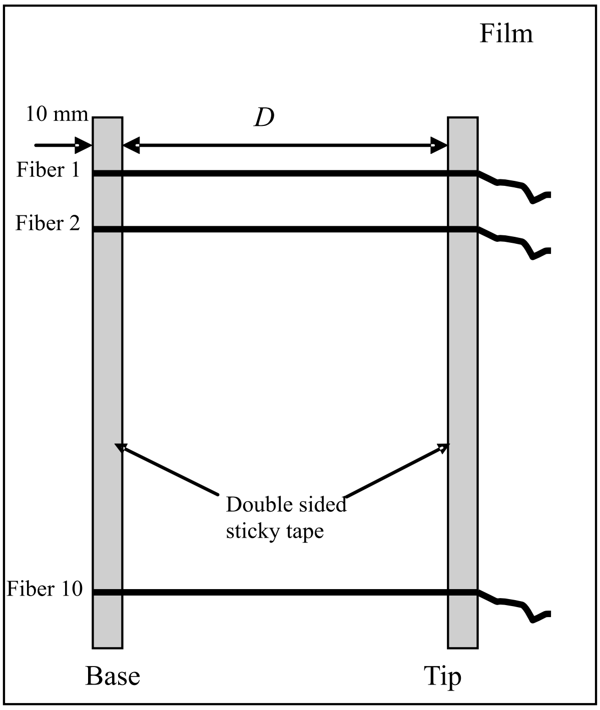

Figure 1 Schematic diagram of the fiber preparation.

Testing Design and Data Processing

The S_fFDPs of each fiber were scanned at four orientations (i.e. 0°, 45°, 90°, and 135°), respectively, by SIFAN3001. The clamps and CCD camera system, as well as a diagram of the scanning principle, are shown in Figure 2. At each orientation, the fiber was firstly decrimped under a 1 cN pre-tension force and the scanning was then conducted along the fiber at a speed of 8 mm/s with a step of 0.2 mm.

The raw diameter data were firstly smoothed by means of a moving average of five diameter results (in over 1 mm length) to remove spurious measurements. Then, for each fiber, the mean diameter at each scanned point (at 0.2 mm increment) was obtained by averaging the (four) measurements generated at the four orientations. Next, for each staple, the average fiber diameter at each scanned point (MFD_{step}) was obtained by averaging the values of 50 fibers from each staple. Finally, the values were compressed for 5 mm increments by averaging the values in the corresponding 5 mm interval.

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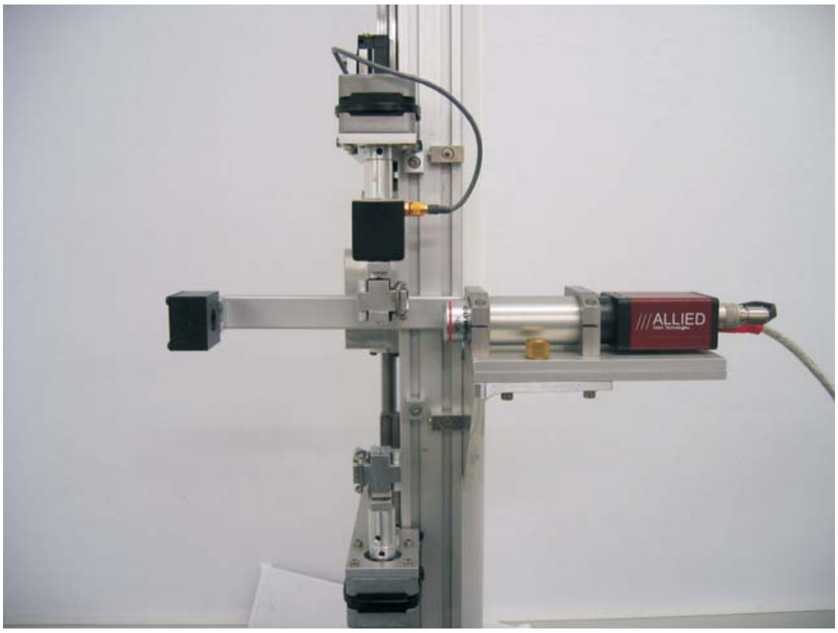
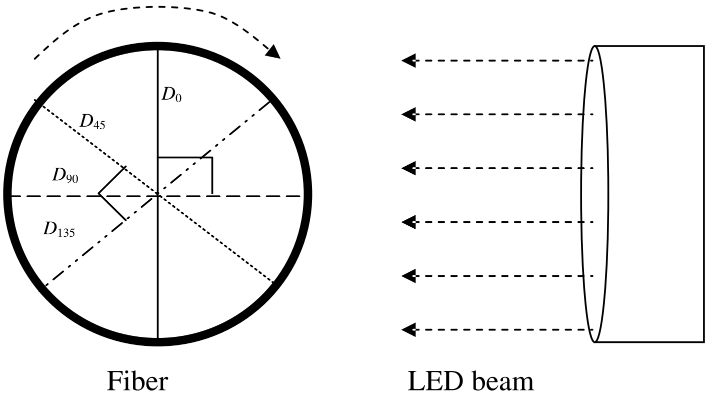


(a)



(b)

Figure 2 Scanning a single fiber by SIFAN3001 at four orientations: (a) the clamps and camera system of SIFAN3001; (b) the scanning model of four orientations.

In order to compare the AS_fFDPs of the staples from each flock, the fiber diameter at each point on the AS_fFDPs was normalized by mean fiber diameter. The nomenclature "*%D*" is used to denote the percentage change from the mean fiber diameter. Meanwhile, the scanned length from the tip end was also normalized by the mean decrimped fiber length, and the nomenclature "*%L*" is used to denote the percentage of the distance from the tip end. Because SIFAN is unable to test the full length of a fiber, the S_fFDP was obtained only over the tested length portion of a fiber. Schematic diagrams of the trial design and data processing are shown in Figure 3.

Taking advantage of measuring four orientations by SIFAN3001, the diameter ratios at each scanned point can be calculated as indicated in Figure 3, where the orthogonal diameters at 0° and 90° were used to calculate Ratio 1, and those at 45° and 135° were used for Ratio 2.

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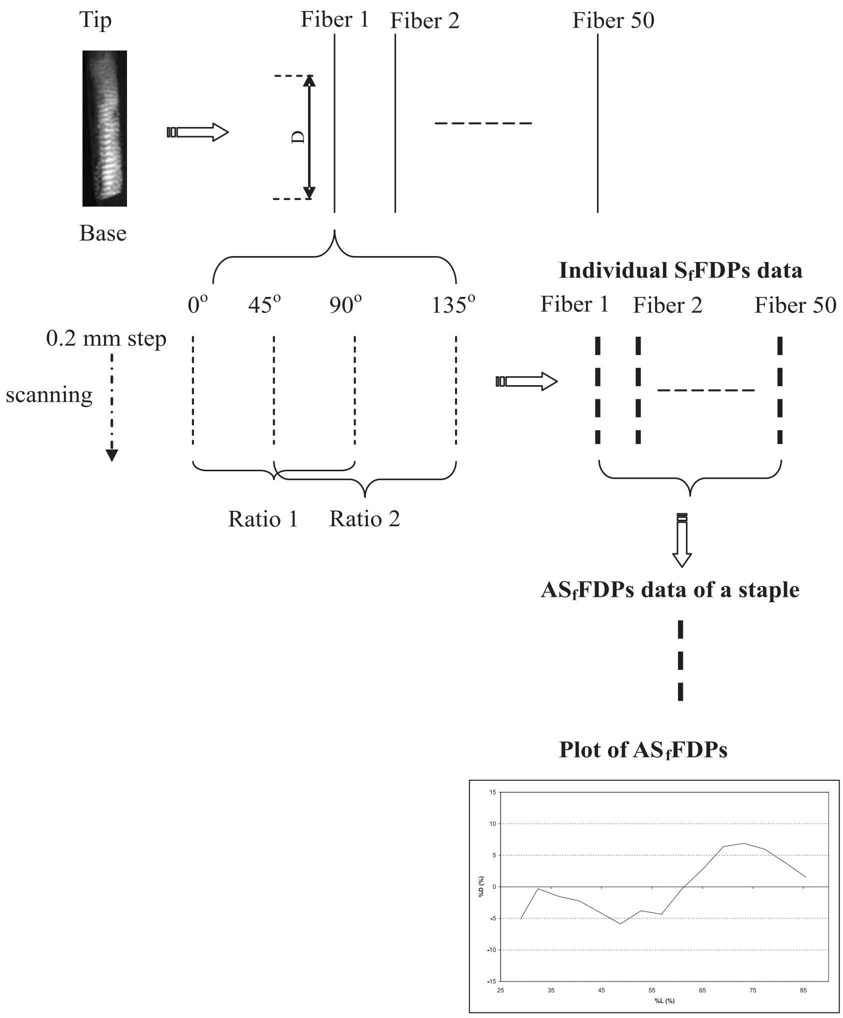

Figure 3 Schematic diagram of trials and data processing.

Table 1 Measurement of diameter for the standard tungsten wires.

	Tungsten wires		
Expected diameter (μm)	10.0	30.0	100.0
Uncalibrated diameter (μm)	10.1	29.5	101.0
Standard deviation (μm)	1.1	1.4	7.4
Testing points	14635	2614	5260

Calibration of SIFAN3001

The SIFAN3001 was calibrated before testing, using standard tungsten wires of different diameters (10, 30, and 100 μm). Table 1 shows the uncalibrated diameters compared with the expected values. These three points were used to derive the slope and intercept of the calibration relationship.

Results and Discussion

Average of Single Fiber Diameter Profiles (AS_fFDPs) of staples

AS_fFDPs for a staple were created by the combination of individual S_fFDPs according to the procedure outlined above. The AS_fFDP plots are shown in Figure 4 for the three flocks. The discussion on the agreement of the S_fFDPs generated by SIFAN3001 and the StFDPs by OFDA2000 is beyond the scope of this paper. Nevertheless, Figure 4 shows the typical characteristics of the AS_fFDPs for each flock.

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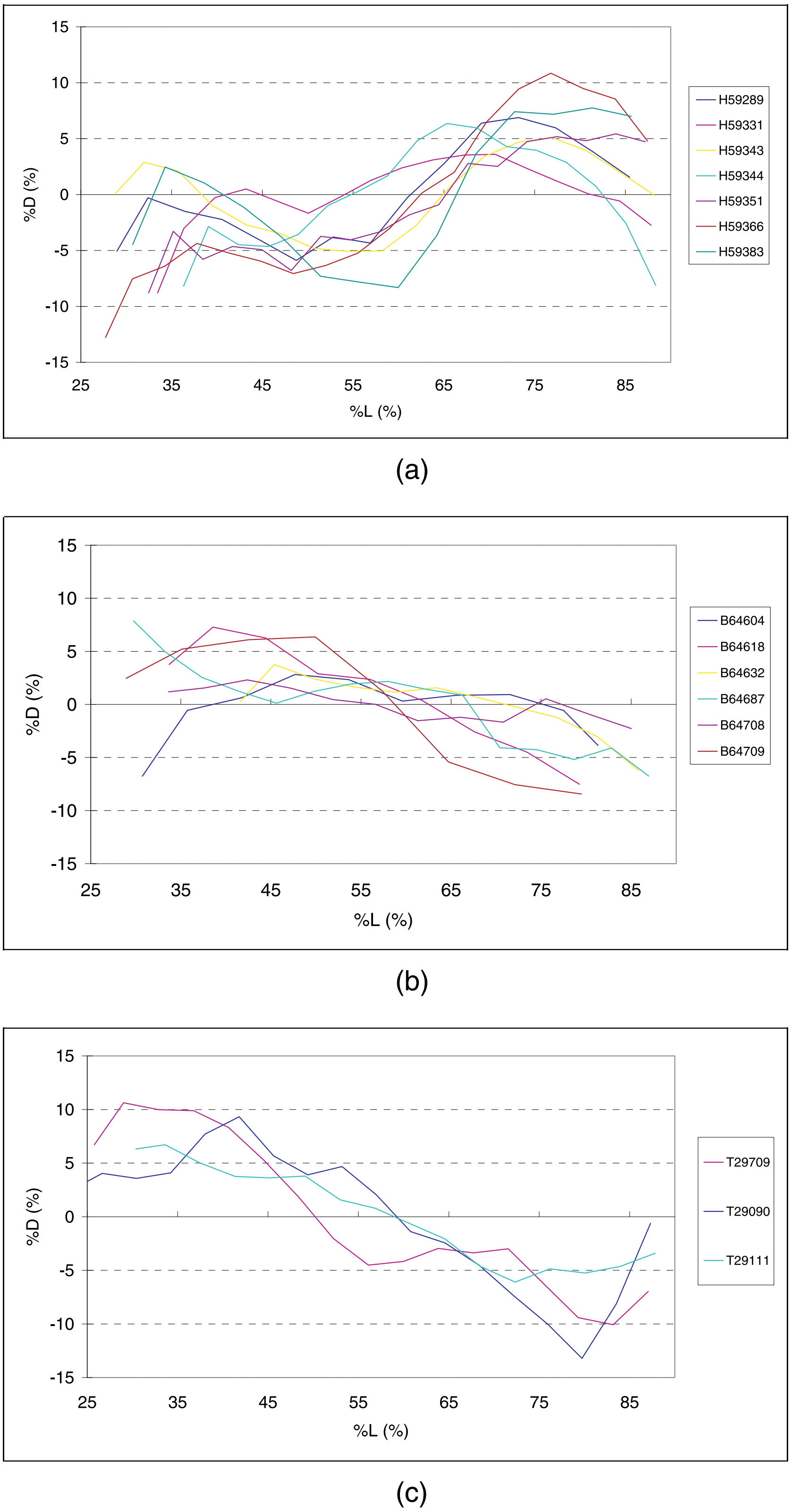

Figure 4 AS_fFDPs of three flocks: (a) Flock H; (b) Flock B; and (c) Flock T.

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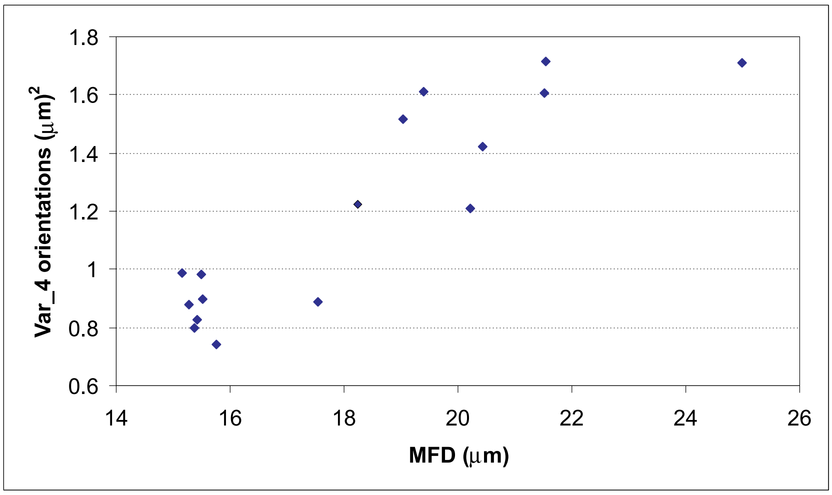

Figure 5 Level dependence of variance between orientations at each scanned step along the fibers.

Table 2 Variance between four orientations for each staple.

Sample	Fiber diameter of four orientations			
	Mean (µm)	SD (µm)	CV (%)	Var $(\mu m)^2$
H59289	18.2	1.0	5.4	1.2
H59331	15.8	0.8	4.9	0.7
H59343	20.4	1.1	5.2	1.4
H59344	21.5	1.2	5.5	1.7
H59351	19.4	1.2	5.8	1.6
H59366	20.2	1.0	4.9	1.2
H59383	17.5	0.9	4.8	0.9
Average	19.0	1.0	5.2	1.3
B64604	15.3	0.8	5.6	0.9
B64618	15.4	0.8	5.5	0.8
B64632	15.5	0.9	5.6	0.9
B64687	15.4	0.8	5.4	0.8
B64708	15.5	0.9	5.9	1.0
B64709	15.2	0.9	6.0	1.0
Average	15.4	0.9	5.6	0.9
T29111	21.5	1.1	6.0	1.6
T29709	19.0	1.2	4.8	1.5
T29090	25.0	1.2	5.5	1.7
Average	21.8	1.2	5.4	1.6

In Flock H, the staples (sheep) had very similar AS_fFDPs. In particular, from the tip to middle, the diameters were finer than the average, whereas from the middle to base, the diameters were broader than the average. The amplitude of *%D* at the tip and base was on a similar level (Figure 4(a)). Both maximum and minimum diameters appeared in phase between the staples.

Flocks B and T demonstrated opposite characteristics in AS_fFDPs compared to Flock H. For both flocks, from the tip to middle, the diameters were broader than the average diameter, whereas from the middle to base, the diameters were finer than the average. The amplitude of *%D* for Flock B was lower than that of Flock T. In addition, the maximum or minimum diameter appeared slightly out of phase between staples (Figures 4(b) and 4 (c)).

Variance Components of the Measurements

Variance of Diameter between Orientations along Fibers

For each fiber, the mean diameter at each scanned step was obtained by averaging the four measurements at different orientations (i.e. 0°, 45°, 90°, and 135°). Therefore, the variance of diameter between orientations along fibers is a measure of the dispersion of the diameters measured at the four orientations from the mean values at each scanned point. The mean, standard deviation (SD), coefficient of variation (CV), and variance of diameter between orientations are listed in Table 2 for each sheep tested.

Table 2 shows that staples from the three flocks had different average MFDs (19.0 µm, 15.4 µm, and 21.8 µm), and variances existed both within and between sheep. The average within the sample variance for each flock was 1.3 $(\mu m)^2$, 0.9 $(\mu m)^2$, and 1.6 $(\mu m)^2$, for Flocks H, B, and T, respectively. Overall, the diameter variance between four orientations at each scanned step along the fibers was level dependent as illustrated in Figure 5; that is, the broader wools had higher variance than the finer wools.

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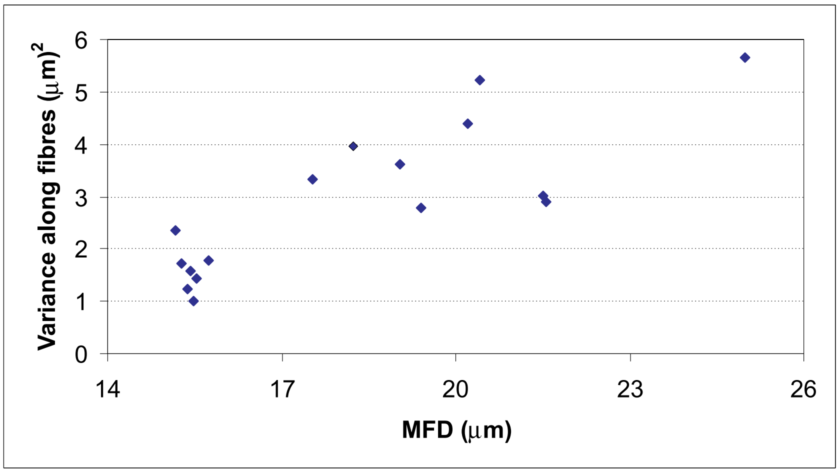

Figure 6 Level dependence of the diameter variance between scanning steps along fibers.

Table 3 Variance of diameter between scanning steps along fibers.

Sample	Diameter along fibers Mean (µm)	SD (µm)	CV (%)	Var (µm)^2
H59289	18.2	1.9	10.4	4.0
H59331	15.8	1.3	8.0	1.8
H59343	20.4	2.1	10.4	5.2
H59344	21.5	1.7	7.9	2.9
H59351	19.4	1.6	8.6	2.8
H59366	20.2	2.0	10.2	4.4
H59383	17.5	1.8	10.2	3.3
Average	19.0	1.8	9.4	3.5
B64604	15.3	1.2	7.6	1.7
B64618	15.4	1.2	7.8	1.6
B64632	15.5	1.0	7.0	1.4
B64687	15.4	1.1	7.0	1.2
B64708	15.5	1.0	6.3	1.0
B64709	15.2	1.5	9.9	2.4
Average	15.4	1.2	7.6	1.6
T29111	21.5	1.7	7.9	3.0
T29709	19.0	1.9	9.8	3.6
T29090	25.0	2.3	9.4	5.7
Average	21.8	2.0	9.0	4.1

Variance of Diameter between Scanning Steps along Fibers

At each scanning orientation, the MFD of individual fibers can be obtained by averaging the fiber diameter measurements at each scanned step. The diameter variance between steps along fibers represents the variation of diameter along fibers. Results along fiber diameters are listed in Table 3. As in the case of between orientation variance, the variance was also level dependent as shown in Figure 6. The along fiber variance was higher than the variance between orientation within fibers, as would be expected.

Variance of Diameter between Fibers within Staples

After the S_fFDP was calculated as indicted in the previous section, an AS_fFDP of each staple can be obtained by combining 50 fibers at each scanned step. Therefore, the diameter variance between individual fibers within staples and the diameter variance between fibers at each scanned step can be analyzed. The results of this analysis are listed in Table 4. The variance between fibers at each scanned step was higher than the overall variance between individual fibers. If the divergent data from staple T29090 are regarded as outliers, the diameter variance between fibers within staples is level dependent (Figure 7).

Variance of Diameter Ratio between the Orthogonal Diameters

In order to examine the ellipticity of individual fibers, the mean fiber diameter ratio for each staple was calculated from the mean diameter ratio of its 50 fibers, which were obtained by averaging Ratio 1 and Ratio 2. The variance of the diameter ratio was estimated for both along fibers and between fibers. The results of these two analyses are listed in Table 5.

The variances in Table 5 are relatively small for a number of reasons, including the following:

- Compared to the variation in diameter readings at each point, the ratio calculation includes two diameter readings.

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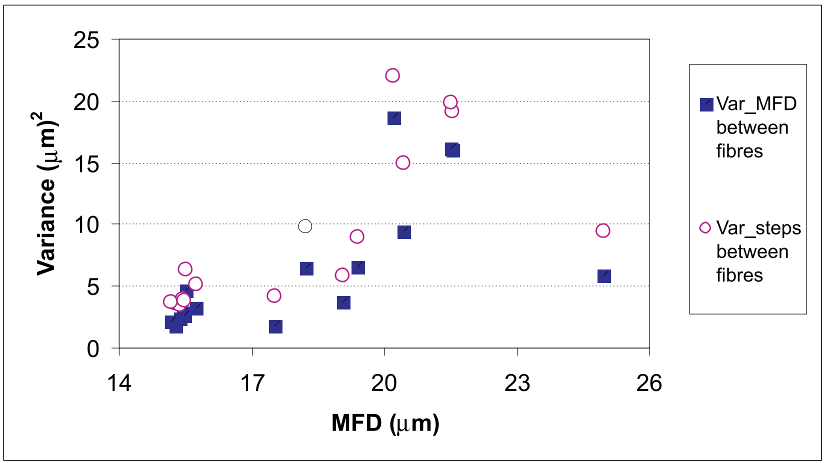

Figure 7 Level dependence of the variance between fibers within staples. (Var_MFD is the variance between mean fiber diameters of 50 fibers; Var_steps is the variance between fiber diameters of 50 fibers at each scanned step.)

Table 4 Variance of diameter between fibers within staples

Sample	Diameter between fibers				Variance between fibers at each scanned step (0.2 mm) (μm)²
	Mean (μm)	SD (μm)	CV (%)	Var (μm)²	
H59289	18.2	2.5	14.0	6.5	9.8
H59331	15.8	1.8	11.4	3.2	5.1
H59343	20.4	3.1	15.0	9.4	15.0
H59344	21.5	4.0	18.6	16.0	19.1
H59351	19.4	2.6	13.2	6.5	9.0
H59366	20.2	4.3	21.4	18.6	22.0
H59383	17.5	1.3	7.7	1.8	4.2
Average	19.0	2.8	14.5	8.9	12.0
B64604	15.3	1.3	8.8	1.8	3.6
B64618	15.4	1.7	10.9	2.8	4.0
B64632	15.5	2.2	13.9	4.7	6.4
B64687	15.4	1.6	10.2	2.4	3.5
B64708	15.5	1.6	10.5	2.6	3.8
B64709	15.2	1.5	9.7	2.2	3.7
Average	15.4	1.6	10.7	2.8	4.2
T29111	21.5	4.0	18.7	16.2	19.9
T29709	19.0	1.9	10.1	3.7	5.9
T29090	25.0	2.4	9.7	5.9	9.4
Average	21.8	2.8	12.8	8.6	11.7

- The average of two ratios was used at each point. It may also be expected that variation in ellipticity along a fiber would be less than variation in diameter along the fiber.

Furthermore, the variance between fibers is much lower than that along fibers. No strong level dependence was found for either the variance along or between fibers.

Precision Estimates of Measurements within the Testing Regime

Precision Estimates of the Measurement for MFD of Staples

As discussed above, the variance components of the fiber diameter measurement for each staple are:

- variance between four orientations within fibers (α^2);
- variance between scanning steps (0.2 mm) along fibers (β^2);
- variance between fibers within staples (χ^2).

Therefore, the precision in terms of 95% confidence limit (95% CL) of the measurement for MFD of each staple can be estimated from the following formula:

$$\text{95\% CL of MFD} = \pm 1.96\sqrt{\frac{\alpha^2}{N_\alpha} + \frac{\beta^2}{N_\beta} + \frac{\chi^2}{N_\chi}} \qquad (1)$$

where N_α is the number of orientations, N_β the number of scans along fibers, and N_χ the number of single fibers subsampled from a staple.

According to the testing regime used, there were 50 single fibers from each staple scanned at four orientations with a 0.2 mm step (meaning approximately 300 readings, i.e. over approximately 60 mm each fiber). The precision estimates of MFD for each staple are listed in Table 6. The precision for MFD measurements is level dependent. The finer wools had a tighter confidence limit than broader wools, as is often observed in MFD measurements of individual sheep, sale lots, and processing consignments of wool.

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Table 5 Variance of diameter ratio along and between fibers within staples.

Sample	Ratio along fibers			Ratio between fibers		
	Mean	SD	Var	Mean	SD	Var
B64604	1.09	0.061	0.0042	1.09	0.033	0.0011
B64618	1.08	0.057	0.0035	1.08	0.030	0.0009
B64632	1.08	0.066	0.0074	1.08	0.041	0.0017
B64687	1.09	0.068	0.0051	1.09	0.029	0.0009
B64708	1.08	0.057	0.0036	1.08	0.032	0.0010
B64709	1.09	0.066	0.0048	1.09	0.035	0.0012
Average	1.09	0.063	0.0048	1.09	0.033	0.0011
H59289	1.08	0.063	0.0042	1.08	0.024	0.0006
H59331	1.07	0.055	0.0033	1.07	0.028	0.0008
H59343	1.08	0.079	0.0232	1.08	0.026	0.0007
H59344	1.09	0.069	0.0065	1.09	0.025	0.0006
H59351	1.09	0.070	0.0050	1.09	0.020	0.0004
H59366	1.08	0.060	0.0043	1.08	0.024	0.0006
H59383	1.07	0.060	0.0048	1.07	0.020	0.0004
Average	1.08	0.065	0.0073	1.08	0.024	0.0006
T29079	1.09	0.078	0.0117	1.09	0.032	0.0010
T29090	1.07	0.056	0.0032	1.07	0.018	0.0003
T29111	1.08	0.070	0.0097	1.08	0.052	0.0027
Average	1.08	0.068	0.0082	1.08	0.034	0.0013

According to the precision calculation, the variance between fibers is a major component contributing to the precision estimate. This result agrees with the findings by Quinnell et al. [14]. These results mean that an improvement in precision (in 95% CL) of a MFD measurement of 14% can be achieved by an increase in the number of single fibers sub-sampled from a staple from 50 to 100.

Precision Estimates of the Measurement for MFD_{step} of the AS_fFDP

According to the calculation of MFD_{step} for generating an AS_fFDP, the components of the diameter variance are:

- variance between four orientations within fibers (α^2);
- variance between fibers at each scanned step within staples (δ^2).

Therefore, the measurement precision of MFD_{step} can be estimated from formula (2) and the results of this calculation are listed in Table 7. Although the variance between fibers at each scanned step is a major component in the total variance, its contribution to the precision estimate is relatively low, due to the relatively high number of fibers (50) tested. Therefore, an increase in the number of scanning orientations will increase the measurement precision for MFD_{step} of the AS_fFDP:

$$95\%\ \text{CL of } MFD_{step} = \pm 1.96\sqrt{\frac{\alpha^2}{N_\alpha} + \frac{\delta^2}{N_\chi}} \qquad (2)$$

Precision Estimate of the Measurement for Mean Diameter Ratio

The variance components of diameter ratio for a staple consist of the variance along fiber (ϕ^2) and the variance between fibers (ε^2). Therefore, the precision of the mean diameter ratio of a staple can be calculated from formula (3) and the results for this trial are listed in Table 8. The precision estimates all staples were the same at ±0.01.

$$95\%\ \text{CL of mean diameter ratio} = \pm 1.96\sqrt{\frac{\phi^2}{N_\beta} + \frac{\varepsilon^2}{N_\chi}} \qquad (3)$$

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Table 6 Precision estimates of MFD of staples ($N_\alpha = 4$; $N_\beta = 300$; $N_\chi = 50$).

Sample	MFD (μm)	95% CL (μm)
H59289	18.2	1.3
H59331	15.8	1.0
H59343	20.4	1.5
H59344	21.5	1.7
H59351	19.4	1.4
H59366	20.2	1.6
H59383	17.5	1.0
Average	19.0	1.4
B64604	15.3	1.0
B64618	15.4	1.0
B64632	15.5	1.1
B64687	15.4	1.0
B64708	15.5	1.1
B64709	15.2	1.1
Average	15.4	1.0
T29111	21.5	1.7
T29709	19.0	1.3
T29090	25.0	1.5
Average	21.8	1.5

Ellipticity of Wool Fibers

The morphological structure of wool cross-sections is important for the measurement of fiber diameter and the evaluation of fiber strength. The effect of ellipticity of wool fibers on the assessment of mean fiber diameter and its coefficient of variation has been investigated by some researchers employing different testing methods [15–17]. Using SIFAN3001 in this paper, the ellipticity of wool fibers was examined by using the average diameter ratio, i.e. the average of Ratio 1 and Ratio 2. It was expected that this technique would yield a lower value than using the ratio of major to minor axes as reported by the authors in the previous three references.

As shown above, the mean diameter ratio of the wool fibers is about 1.08 ± 0.01. This mean value is relatively low, because the technique used to obtain the diameter ratio does not identify the major and minor axes but simply records the diameter ratio of two randomly selected orthogonal orientations. Nevertheless, this mean value still indicates that the cross-section of wool fibers appears to be elliptical rather circular as a normal assumption. The elliptical morphology of wool fiber cross-sections will need to be considered in the development of a mechanical model of SS testing.

Table 7 Precision estimate of MFD_{step} of AS_fFDP ($N_\alpha = 4$; $N_\chi = 50$).

Samples	Variance between four orientations within fibers (μm)^2	Variance between fibers at each scanned step within staples (μm)^2	95% CL (μm)
H59289	1.2	9.8	1.4
H59331	0.7	5.1	1.0
H59343	1.4	15	1.6
H59344	1.7	19.1	1.8
H59351	1.6	9	1.5
H59366	1.2	22	1.7
H59383	0.9	4.2	1.1
Average	1.3	12.0	1.4
B64604	0.9	3.6	1.1
B64618	0.8	4	1.0
B64632	0.9	6.4	1.2
B64687	0.8	3.5	1.0
B64708	1.0	3.8	1.1
B64709	1.0	3.7	1.1
Average	0.9	4.2	1.1
T29111	1.6	19.9	1.8
T29709	1.5	5.9	1.4
T29090	1.7	9.4	1.5
Average	1.6	11.7	1.6

Conclusion

The results reported here show that using SIFAN3001 to measure fiber diameter at four orientations for 50 single fibers randomly sub-sampled from each mid-side sample can produce average single fiber diameter profiles of staples. The average single fiber diameter profiles showed reasonable agreement between staples within flocks, and typified the major characteristics of the fiber diameter profiles of the flocks.

The precision estimates within the testing regime used in this paper showed that the measurements for mean fiber diameter of staples and mean fiber diameter at each scanned step of the average single fiber diameter profiles were within reasonable confidence limits, ±1.3 μm

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Table 8 Precision estimates of mean fiber diameter ratio (N_β = 300; N_χ = 50).

Sample	MFD (μm)	Mean ratio	95% CL
B64604	18.2	1.09	0.01
B64618	15.8	1.08	0.01
B64632	20.4	1.08	0.02
B64687	21.5	1.09	0.01
B64708	19.4	1.08	0.01
B64709	20.2	1.09	0.01
Average	17.5	1.09	0.01
H59289	19.0	1.08	0.01
H59331	15.3	1.07	0.01
H59343	15.4	1.08	0.02
H59344	15.5	1.09	0.01
H59351	15.4	1.09	0.01
H59366	15.5	1.08	0.01
H59383	15.2	1.07	0.01
Average	15.4	1.08	0.01
T29079	21.5	1.09	0.01
T29090	19.0	1.07	0.01
T29111	25.0	1.08	0.02
Average	21.8	1.08	0.01

for mean fiber diameter profiles, and 1.4 μm for the mean fiber diameter profiles at each scanned step in the fiber diameter profile. The variance between fibers within staples was a major component in the precision estimate for mean fiber diameter profiles. All variance components of the diameter within staples were level dependent.

The mean diameter ratio of 1.08±0.01 obtained from the four orientation testing confirmed that the Merino wool fibers under review were elliptical rather than circular. The elliptical morphology of wool fibers and the precision of fiber diameter measurement at each point along a fiber will be considered in the development of a mechanical model of SS testing.

Acknowledgment

The authors would like to express sincere thanks to Australian Wool Innovation Ltd for its support of this work.

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