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NEXT GENERATION WOOL QUALITY

2.3 Desirable, Specified Handle in Merino Wool Fabrics

R4.3.3.5 Final report on genetic and environmental contributors to fabric handle - morphological and physical properties of wool fibres from 2007 drop INF progeny

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Executive summary

The objective of this work is to determine if fibre properties other than fibre diameter and fibre curvature have a significant influence on softness of handle of clean wool. If any effects are identified, these will be quantified and their genetic properties investigated. This is the final report on the investigation of the surface properties (scale height, scale length and roughness) and physical properties (fibre shape/ellipticity and surface friction) from sheep selected from the CRC Information Nucleus Flocks (INF). Mid-side samples, matched for diameter and curvature, exhibiting extremes in Resistance to Compression, and different subjective handle scores were selected from the 2008 shearing of the 2007 drop Merino progeny. Further subjective handle testing and a felt ball test were conducted on the solvent cleaned samples. The most easily felted sample was neither the softest nor the finest of the wools tested, but it did possess the lowest fibre curvature. Based on paired comparison assessments of cleaned wool samples a significant difference in handle was observed between a pair of 15.5µm samples with a curvature of 101°mm^{-1}. Fibres extracted from these two samples were subjected to individual fibre testing for ellipticity, macro-friction and nano-scale measurements of fibre's scale properties using the scanning probe microscope. The results reported here show that the difference in the handle observed for the pair of 15.5µm wool samples with a curvature of 101°mm^{-1} was related to differences in the cuticle topography of the fibres and not differences in bending stiffness.

Phenotypic and genetic correlations between fibre diameter, curvature, RtC and handle were estimated by Hatcher (2010). The phenotypic correlations between these traits were low, less than 0.41, and the genetic correlations were larger except for fibre curvature. The heritability estimate for handle was 0.86. The estimated breeding value for handle for 32 sires ranged from -1.04 to 0.86.

Introduction

Traditionally wool has been used in mid and outer layer clothing such as tailored formal wear, winter weight jackets and jumpers to provide warmth during the cooler seasons of the year. As a result, wool is typically regarded as a winter fibre. Our active lifestyles and increased leisure time have resulted in a shift in global clothing consumption away from formal tailored wool garments towards sporty, active, casual clothing. Similarly, our improved living standards in our climate controlled homes, cars and workplaces are shifting our clothing choices towards lighter weight, 'next-to-skin' knitwear garments that are trans-seasonal and can be worn year round. Wool currently has little presence in this rapidly growing trans-seasonal, next-to-skin knitwear market which is currently dominated by cotton and synthetic fibres. To broaden the consumption of wool by making wool competitive in this market, it is necessary for wool to have an appealing, if not luxurious hand (softness). The fibre properties responsible for the hand of Australian Merino wool need to be identified so that it may be feasible to select sheep for their wool softness.

Stevens (1994) associated the softness of textiles with having both a smooth/fine textured surface and being easily deformed (yielding) under pressure. The softness results from the interaction between the fibres and the response of the individual fibres to stress. Restriction of fibre movement in a sample will reduce softness. In the case of loose wool, a smooth fibre surface would be expected to reduce inter-fibre friction and allow the fibres to slide more easily against each other and over the skin. Greater flexibility allows fibres to bend more easily and hence have a softer handle. The fibre bending or flexural rigidity (stiffness), B, is defined as the couple required for bending the fibre to unit curvature. It is a measure of the fibre's resistance to bending (Morton and Hearle, 1993). For elliptical fibres it can be assumed that fibres will preferentially bend about their minor elliptic axis (Swift, 1995, Wortmann and Schwann-Jonczyk, 2006) and the bending stiffness is given by Equation 1, where E is the tensile modulus, e = a/b is the fibre ellipticity. The fibre ellipticity is the ratio of the major axis and minor axis of the ellipse, where *a* is half the major axis and *b* is half the minor axis.

$$B = \frac{E\pi a^4}{4e^3} \tag{1}$$

It is clear that the fibre diameter is the most important fibre parameter influencing the bending rigidity, and a small change in diameter will result in a noticeable change in flexibility. Based on Equation 1, if one was selecting fibres for softness, one would chose fibres that have a low fibre diameter, low tensile modulus and have a more elliptical cross sectional shape.

It is generally accepted that softness of wool is dependent on the diameter of the fibre (MFD), and the significant role of fibre diameter in influencing the softness of loose wool fibres has been confirmed by several landmark studies (Ali et al., 1971, Shah and Whiteley, 1971, Smuts and Slinger, 1972). These researchers also confirmed the relationship between softness and diameter was found to be valid both within and between breeds of sheep. Nevertheless, fibre diameter alone could not fully explain the differences in the perceived softness of their samples and Resistance to Compression (RtC) was found to be the most important secondary factor, with staple or fibre crimp characteristics significant through their influence on the compressibility of the fibre bulk. These researchers studied a broad range of fibre diameters and were not able to find a significant relationship between softness and the frictional properties of the wool fibres. When Smuts (1972) added mohair, karakul and goat hair, the against scale friction became a significant factor and accounted for some of the variation in softness.

Teasdale et al. (1985) could not find any significant relationships between the handle of cashmere and its diameter, coefficient of variation of diameter or RtC. He concluded that selection for softness based on mean fibre diameter alone was not possible and suggested that ‘there may be a contribution from some other source such as fibre shape, surface or substance’.

Roberts (1956) and Shah and Whiteley (1971) examined the contribution of substance on handle, but were unable to find a significant relationship between hand and the material property as indicated by the Young’s or bending moduli.

Other researchers have studied the correlation between felting propensity, softness and scale structure with the hypothesis that scale structure influences both the tactile and physical properties of wool fibres. Kenyon (1999) found that softness accounted for 19% of the total variation in loose wool felting. Ladyman (2004) found that scale height contributed to differences in felting ability of low curvature wools. Sumner (2009) used a scanning electron microscope technique to measure cuticle properties such as scale height, length and width of six different breeds of sheep and found that fibre diameter was the dominant characteristic and accounted for 84% of the variation in wool softness, whilst feltability was influenced by the combined effect of fibre diameter, fibre curvature, scale height and scale length.

Currently there is no specific objective test method available for the measurement of bulk fibre softness, and RtC is generally considered to be the best indicator of softness of loose wool (Madeley and Postle, 1999, Madeley et al., 1998). There is also evidence that the bulk softness of loose wool can be translated into the handle of fabrics made from the wool (Madeley et al., 1995, Stevens and Mahar, 1995). In the first case fabric softness rankings were related directly to RtC results for knitted woollen fabrics, with softness ranking decreasing as loose wool RtC increased from approximately 7kPa to 15kPa. In the second case samples composed of wool matched for fibre diameter but of different values of staple crimp were measured for RtC, with low staple crimp being related to low RtC. These samples were processed into woven worsted fabrics subjective assessments of which showed that low RtC samples were significantly smoother than high RtC samples of similar diameter.

Clearly softness is important for the value of wool and a price premium is paid for fine wool fibres, largely due to the contribution of fibre diameter on softness and wool fabric handle

(AWI website). Given the shift towards finer fibres over the last few decades (Cottle, 1991, Anon, 2007), and that most of the research relating fibre properties to softness was conducted before fibre diameter and curvature could be objectively measured, it is important to re-examine the fundamental relationships between subjectively assessed fibre handle and objectively measured fibre properties for wool across the current Australian Merino flock. The CRC Information Nucleus Flocks (INF) affords an opportunity to examine these relationships, including the genetic and environmental details of the INF sheep, and test if other factors other than diameter and curvature can be shown to affect softness (RtC).

Approach of this study

Accepting that MFD & MFC are the main determinants of RtC (Swan, 1993, Van Wyk, 1946, Shah and Whiteley, 1971) and that RtC measures loose wool softness, the main aim of this study is test the hypothesis that secondary fibre properties other than diameter and curvature can influence softness (RtC). This study focuses on wools that show marked deviation in RtC, when the effects due to fibre diameter and curvature are removed. Our earlier study (Hillbrick and Huson, 2008) showed that tensile stiffness (Young’s modulus) and RtC (softness) were not significantly related and that tensile modulus of wool was dependant on the diameter of the wool fibre. Hence when diameter and curvature are constant, increased softness may be due to a reduction in bending stiffness as a result of increased fibre ellipticity and/or a reduction in the frictional properties allowing the fibres to slide more freely.

The surface properties (scale height, scale length and roughness) and physical properties (fibre ellipticity and surface friction) of wool fibres selected from 2008 shearing of the CRC Information Nucleus Flocks (INF) initial drop of 2007 Merino progeny. In view of the detailed single fibre measurements that were to be made on each sample, testing was limited to a small selection of mid-side samples matched for diameter and curvature and divergent (high and low) RtC.

This report summarises the relationships between greasy hand and the fibre characteristics of the Information Nucleus Flocks (INF). This paper also reports on the findings of the detailed investigation of selected samples including a comparison of their subjective softness after solvent cleaning, the morphological properties (cuticle step height, nano-roughness and frequency) measured by Scanning Probe Microscopy (SPM) and physical properties (fibre shape/ellipticity and macro-scale friction). The felting propensity of the selected samples is also quantified in this study because of the earlier suggestion by Sumner (2009) that scale structure influences both the tactile and physical properties of wool fibres.

Experimental Details

CRC Information Nucleus Flocks

The Sheep CRC established eight, research flocks across Australia, referred to as Information Nucleus Flocks (INF) (Forgarty et al., 2007). The flocks are known as IN01 (Kirby), IN02 (Trangie), IN03 (Cowra), IN04 (Rutherglen), IN05 (Hamilton), IN06 (Struan), IN07 (Turretfield) and IN08 (Katanning). The genetic details of these flocks are known, and objective and subjective data for the 2008 shearing of the 2007 drop was made available in August 2009 for the purpose of studying the relationships between subjectively assessed fibre handle and fibre diameter, curvature and resistance to compression. The 2007 IN drop comprised of 1265 MM progeny (Smith, 2009). Trangie (IN02) did not have a Merino drop in 2007 due to drought. Objective testing of mid-side samples taken at the time of shearing was carried out by the Australian Wool Testing Authority Ltd (AWTA) using standard SA/SNZ test methods. The suite of objective tests included resistance to compression (RtC), Laserscan fibre diameter (MFD), coefficient of variation of fibre diameter (CVD), Laserscan fibre curvature (MFC), Atlas staple strength (SS) and length (SL), clean colour and yield . The only objective measurements conducted on all sheep across all sites were Laserscan (MFD and MFC) and RtC. Staple length and strength were measured only on samples from IN01, IN05 and IN07. The subjectively assessed attributes included hand, greasy colour, character, dust, weathering and fleece rot. These attributes were scored on a scale of one to five, where a score of one represented a very desirable attribute and a score of five was highly undesirable attribute. Hand, or handle, was an optional assessment and was scored at only three sites (IN01, IN07 and IN08). The protocol used for the assessment of hand of the fleece whilst on the sheep was described by Hatcher (2010) and involved stroking a mid-side staple from the base to the tip. Microsoft Office Access 2003 was used to manage data and Microsoft Office Excel 2003 was used for correlation and regression studies. The correlation between diameter, curvature and RtC was determined across all sites, whereas correlations between subjective hand and the major fibre properties of namely diameter, curvature and resistance to compression where restricted to sites that measured hand.

There were inconsistencies in shearing protocols across sites that resulted in some sheep being tip shorn at IN03, IN04, IN06 and IN08 whilst sheep at IN01, IN05 a IN07 were not tip shorn (Smith, 2009). At the IN03 and IN04 sheep were tip shorn at weaning and the wool samples were taken from the yearlings with only 6 - 7 months of wool growth. Similarly at IN06 (retain group) and IN08 sheep were also tip shorn, but wool samples were taken with 11 – 12 months of wool growth. The IN01, IN05, IN07 and IN06 (slaughter group) were not tip shorn, rather shorn at 10 – 11 months, so samples have about 10 – 11 months of growth. It is possible that the presence of the lambswool tip may influence some of the measured objective and subjective traits (Madeley, 1994).

Dr Sue Hatcher (2010) estimated the phenotypic and genetic correlations between subjective hand and diameter, curvature and RtC.

Four pairs of samples matched as closely as possible for diameter and curvature and exhibiting extremes in RtC were selected further analysis, since it is expected that these samples should show differences in softness in loose wool form. Only the mid sections of these fibres were used in the detailed examinations to avoid the weathered tips and/or the presence of lambswool tips.

Fibre Diameter and Curvature of selected samples

A Sirolan-Laserscan (IWTO 12) was used to confirm the diameter and curvature details of the eight selected INF wools. Random staples were extracted from the greasy mid-side samples and guillotined into snippets, 2 mm long in length. The snippets were scoured by soaking in tetrachloroethylene for 2 minutes. The solvent was removed in the Sirolan-SD snippet drier and snippets were dried overnight in an oven set at 50 °C, then conditioned in a standard atmosphere of 20 °C and 65% relative humidity for 24 hours before testing on the Laserscan. One Laserscan measurement was performed and a total of 2000 counts were used for each measurement.

Cleaning procedures used for greasy mid-side samples

For ellipticity and friction studies wool staples were cleaned by a gentle, four bath aqueous scour. All baths were set at 65 °C and the first three baths contained 0.05 % w/v, 0.05 % w/v and 0.025% w/v, Lissapol TN450 (ICI) respectively. The final bath contained water only. Each sample comprising of three staples was scoured sequentially through the four bath scour. Staples were held securely to prevent felting and were scoured one at a time by immersing the sample in the baths using a gentle up and down motion. The sample residence time in the first three baths was one minute and two minutes in the final bath. Between baths, excess liquor was removed by gentle squeezing. Fresh scouring baths were prepared for each different sample.

For subjective softness testing and felt ball testing, 10 g of each greasy INF wool was cleaned by solvent extraction in 180 mls of dichloromethane for 3 hours at 105 °C using a Soxtherm (Gerhardt) extraction unit, then after drying and conditioning the degreased wools were Shirley carded to remove residual dust and vegetable matter.

In order to characterise the wool fibre surface at the nano-scale using AFM, stringent cleaning methods were required to remove all unbound lipid contamination. Fibres cleaned using the Soxtherm method were too contaminated for further AFM studies and required an additional gentle scour in Lissapol TN450 (ICI) detergent followed by a 5 hr soxhlet extraction with chloroform / methanol (2:1 azeotrope) cycling 5 times per hour. This method was found to remove any residual contamination or free lipid material on the surface.

Subjective handle of degreased wools

Six INF wools which had scores given for greasy hand, were used for the subjective appraisal. The samples were cleaned by solvent extraction in the Soxtherm (Gerhardt) extraction unit and Shirley carded (as described above). The softness of the cleaned 1g wool samples were tested using a multiple paired comparison by ten judges. Prior to subjective assessment, samples were conditioned in a standard atmosphere of 20 °C and 65% relative humidity (RH) for 24 hours. Subjective assessments were also conducted under the same atmospheric conditions. To avoid visual bias, judges were not able to see the samples. Two samples were presented consecutively to a judge who was asked to identify the softer sample of the pair of samples. Each pair was presented twice to each judge. All 15 possible pairs of the six INF samples were evaluated by each judge. The order of presentation was random and different for each judge. The judges were chosen from a group of volunteers used for prickle evaluation and were familiar with subjective testing. No detailed instructions or definitions of softness were given to the judges and samples were replaced for every third judge. The results were analysed using a Friedman Ranked Sum analysis and the rank sums were compared at $\alpha = 0.05$ using Tukey's HSD (honestly significant difference) method (Meilgaard (1987).

Felting Propensity

The greasy INF wools were soxhlet extracted in dichloromethane for 3 hours at 105 °C using a Soxtherm (Gerhardt) extraction unit, then after drying and conditioning, were Shirley carded to remove residual dust and vegetable matter.

Six x 1g samples of the open web of fibres were preformed into balls and agitated in 50mls of pH 6.8 buffer solution in a Labomat for 30 minutes at 60 rpm with 25 steel ball bearings. The temperature of felting was set at 40 °C. At the conclusion of felting the feltballs were dried overnight in an oven set at 50 °C. The diameters of the feltballs were measured in three orthogonal planes and the average for each sample including its 95% confidence interval was recorded.

Ellipticity of fibre cross-sections (fibre shape)

Aqueous scoured single fibres were randomly selected and pre-tensioned with a 300 mg weight, to de-crimp the fibres. The mid sections of the tensioned fibres were embedded in Spurr's firm resin and cured at 60 °C for 18 hours. Transverse sections, perpendicular to the fibre axis, were cut from the resin block using a 45° Diatom Ultrathin diamond knife mounted on a Riechert-Jung microtome using a 6° clearance angle and a cutting speed of 1 mm/sec. Sections approximately 1.5 μm thick were placed onto glass microscope slides and transmission electron microscope grids for future analysis. The smooth residual block face was imaged on a Leitz Dialux 22 microscope using incident light. A Leica DC300F digital camera was attached to the microscope using a 1x c-mount, calibrated with a 2 mm Leica graticule with 1 interval equivalent to 0.01 mm. Photomicrographs of the transverse fibre cross-sections were recorded and the ellipticity was estimated from the ratio of the length of the major axis to minor axis (orthogonal feret) as measured by the image detect and feature binary edit functions of the Leica QWin Pro Version 3.3.1 image analysis system. The ellipticity was measured for approximately 20 fibres per sample.

Macro-scale fibre to metal friction

Fibre to metal friction was measured by a capstan method similar to that used to measure fibre to metal-pin friction (Eley J.R. et al., 1985). Instead of using a 20mm pinned cylinder, a 5 mm diameter, solid, stainless steel cylinder was used as the metal test surface. An aqueous scoured single wool fibre was attached to a cantilever connected to a strain gauge. The fibre was wrapped through an angle of 180 degrees around a stainless steel cylinder as shown in Figure 1, and a 500 mg tensioning weight was attached to the other end of the fibre. The cylinder was rotated at 250 rpm and the tension difference in the fibre was measured after 10 seconds of rubbing was recorded. The coefficient of friction, µ, was calculated from the two tension readings according to equation 2. The fibre was them reversed so that with scale and against scale coefficients of friction could be calculated. The test was performed on twenty randomly selected fibres that had been cleaned by dichloromethane Soxtherm solvent extraction.

$$\mu = \frac{1}{\pi}(\ln\frac{T_1}{T_0}) \tag{2}$$

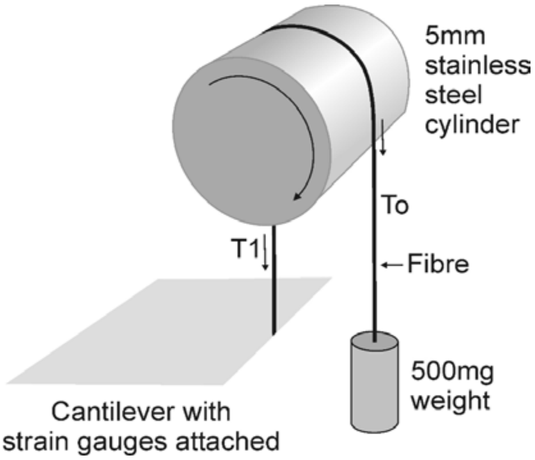

Figure 1: Schematic of apparatus used to measure fibre to metal friction

Surface Properties: Cuticle step height, scale frequency and surface roughness

Surface characterisation was performed on a Digital Instruments Dimension 3000 Scanning Probe Microscope (SPM) operated in Tapping-ModeTM, using a silicon point probe (spring constant of 42 N/m). The scanner was calibrated for the X, Y, & Z directions using the 10µm x 10µm pitch grating with 200nm deep pits. Ten random fibres per sample were mounted onto microscope slides so that the mid-sections of the fibres were held securely on double-sided tape. Measurements were carried out in air under ambient conditions of about 21 °C and 55% relative humidity. After engagement of the tip with the surface of the fibre, the tip was scanned with the fast axis (horizontal axis of the image in the software) parallel to the longitudinal axis of the fibre. For cuticle step height and frequency determinations, height images were obtained by scanning the tip over a 60µm length using a scan rate of 0.25Hz and a 4:1 aspect ratio and a resolution of 256 data points per line. In each 60µm region there were numerous scale edges present, and for each fibre, three different 60µm regions were scanned. Images were processed using a third-order flatten command that removed tilt, curvature and S-shape curvature from each scan line. Each individual cuticle step height was determined using the average cursor technique that measures the height differential parallel to the scale edge over a distance of approximately 5µm. Cuticle step heights (approximately 200 per sample) were averaged to obtain the average cuticle step height for the sample. The distances between the scale edges was used as measure of scale length and the scale frequency was determined from the number of scales edges in each 60µm section. For scale roughness determinations, the tip was scanned in between the scales edges. Height images were obtained over a 5µm x 5µm scan size using a scanning rate of 1Hz and 256 data points per line. These height images were also processed using a third-order flatten and surface roughness was determined using Nanoscope (V5.31) software over the entire height image. The surface roughness was quantified in terms of root-mean square roughness (RMS) which represents the standard deviation of the Z values within the measurement area. For comparative analysis of roughness it is important to apply the same protocol before measurement of roughness, as different values are obtained depending on how the data are pretreated.

Results and discussion

Descriptive statistics for the 2008 shearing of the 1265 INF Merino progeny from the 2007 drop are provided in Table 1. The count reflects the number of sheep that were tested for specific parameters. The varying number of counts reflects that not all parameters were measured on all sheep at each site. The confidence level refers to the 95% confidence interval of the samples tested.

Subjective hand (softness) was scored at only three sites, IN01 (Kirby), IN07 (Turretfield) and IN08 (Katanning) totalling only 597 assessments. Hand was scored using a scale between one and five, where a score of one represented a very soft fleece and a score of five represented a very harsh handling fleece. Hand was scored by different assessors at each site and descriptive statistics for sheep with greasy hand scores for the three sites are also given in Table 1. The average greasy hand across the three sites was 2.7.

Kirby had the finest average fibre diameter (16.08 µm) of the three hand scoring sites and its average greasy hand score was significantly less than Turretfield and Katanning ($P<0.001$). Interestingly the average greasy hand scores and the average MFC of Turretfield and Katanning were not significantly different ($P=0.23$ and $P=0.78$ respectively), yet their average fibre diameters were 16.6 µm and 18.2 µm respectively and their average RtC values were significantly different ($P=0.03$).

Fine diameter fibres are generally softer handling than coarse fibres and a simple plot of mean fibre diameter against hand score in Figure 1 confirmed the trend that as fibre diameter increases, the hand of fibres becomes harsher. Figure 1 and Table 2 also show the mean fibre diameter for each hand score at each site. At Kirby, the majority of sheep (54%) were given a hand score of 2. At Turretfield, 65% of sheep were given a hand score of 3. At Katanning, 43% of sheep were given a hand score of 3, 27% received a hand score of 2 and 19% received a hand score of 4. Katanning was the only site to give some sheep a hand score of 5.

Table 1: Descriptive statistics for INF progeny (2007 drop, 2008 shearing, n=1265) across all sites and for sites with greasy hand scores (Kirby, Turretfield and Katanning)

		MFD µm	CVD %	MFC °/mm	RTC kPa	SL mm	COL score	CHAR score	DUST score	HAND score
All INF sites	Mean	17.03	18.18	57.58	7.75	75.64	2.45	2.62	2.65	2.70
	Standard Deviation	1.71	2.73	8.60	0.75	10.13	0.86	0.88	0.74	0.81
	Sample Variance	2.93	7.43	73.92	0.57	102.67	0.74	0.78	0.55	0.65
	Minimum	12.5	12.0	35	4	47	1	1	1	1
	Maximum	27.7	29.8	98	12	104	5	5	5	5
	Count	1265	1265	1265	1265	508	1207	1207	1207	597
	Confidence Level (95.0%)	0.09	0.15	0.47	0.04	0.88	0.05	0.05	0.04	0.06
IN01-Kirby#	Mean	16.08	17.33	62.55	8.05	78.92	3.15	3.09	2.20	2.36
	Standard Deviation	1.19	2.43	8.28	0.80	10.14	0.63	0.70	0.48	0.69
	Minimum	12.9	12.4	44	6	53	2	1	1	1
	Maximum	20.3	25.7	98	11	103	5	4	4	4
	Count	214	214	214	214	214	214	214	214	214
	Confidence Level (95.0%)	0.16	0.33	1.12	0.11	1.37	0.08	0.09	0.06	0.09
IN07-Turretfield#	Mean	16.55	19.90	55.30	7.71	71.34	2.03	2.48	3.27	2.94
	Standard Deviation	1.31	2.70	6.99	0.70	8.66	0.36	0.65	0.46	0.62
	Minimum	13.1	13.9	35	6	50	1	1	2	1
	Maximum	21.8	29.8	85	10	94	3	4	4	4
	Count	181	181	181	181	181	181	181	181	181
	Confidence Level (95.0%)	0.19	0.40	1.03	0.10	1.27	0.05	0.09	0.07	0.09
IN08-Katanning#	Mean	18.16	17.29	55.53	7.88		2.56	2.72	2.44	2.85
	Standard Deviation	1.63	2.37	9.09	0.77		0.88	0.94	0.79	0.94
	Minimum	14.5	12.9	36	4		1	1	1	1
	Maximum	27.7	25.9	90	12		5	5	5	5
	Count	202	202	202	202	0	202	202	202	202
	Confidence Level (95.0%)	0.23	0.33	1.26	0.11		0.12	0.13	0.11	0.13

data from sheep with greasy hand scores were used to calculate site averages

MFD is mean fibre diameter, CVD is the coefficient of variation of fibre diameter, MFC is mean fibre curvature, RTC is the resistance to compression, SL is the staple length, COL, CHAR, DUST and HAND are the colour, crimp character, dust penetration and hand scores respectively for the greasy raw wool

Table 2: Descriptive statistics for the average fibre diameter for each hand score at each site

		Hand score				
		1	2	3	4	5
IN01-Kirby[#]	Mean fibre diameter (µm)	15.60	15.94	16.24	17.37	
	Standard Deviation	1.00	1.06	1.32	1.08	
	Minimum	14.1	12.9	13.5	15.9	
	Maximum	17.2	19.2	20.3	19	
	Count	16	116	72	10	
	Confidence Level (95.0%)	0.53	0.19	0.31	0.77	
IN07-Turretfield[#]	Mean fibre diameter (µm)	16.55	16.22	16.32	17.90	
	Standard Deviation	1.34	0.99	1.13	1.59	
	Minimum	15.6	14.3	13.1	14.7	
	Maximum	17.5	19.1	20	21.8	
	Count	2	34	117	28	
	Confidence Level (95.0%)	12.07	0.34	0.21	0.62	
IN08-Katanning[#]	Mean fibre diameter (µm)	16.59	17.46	18.30	18.78	21.84
	Standard Deviation	1.14	0.88	1.27	1.41	3.70
	Minimum	14.8	15.3	14.5	15.2	18
	Maximum	18.8	19.2	21.4	23.4	28
	Count	15	54	87	39	7
	Confidence Level (95.0%)	0.63	0.24	0.27	0.46	3.42

The correlation matrix for mean fibre diameter, curvature and RtC for the 1265 Merinos from the 2007 Merino drop is shown in Table 3. The correlation coefficients between RtC and curvature, and RtC and diameter were 0.49 (P<0.001) and 0.28 (P<0.001), respectively. These results are in good agreement with values reported as early as 1946, when staple crimp frequency and fibre diameter had been identified as the main determinants of RtC (Van Wyk, 1946). In that work a correlation of 0.55 was obtained between RtC and staple crimp frequency. More recently Kurdo (1985) found the correlation between RtC and fibre diameter was 0.25 (P<0.001) for a flock of 638 sheep,. In a subset of 20 sheep, he found the correlation between RtC and staple crimp frequency was 0.59 (P<0.001). Wilkins et al. (1981) also found that RtC correlated more strongly with staple crimp frequency (R=0.47) than fibre diameter (R=0.39). Fibre curvature relates directly to staple crimp frequency and as frequency increases, the fibres are increasingly (Fish et al., 1999). Hence it is not surprising that similar correlations were obtained.

The correlation matrix for subjective raw wool hand score (n=597) and various fibre parameters are given in Table 4. The fact that the dependent variable (hand score) is derived from a ranking procedure means that caution needs to be exercised, particularly regarding the use of the regression equations (Ali et al., 1971). The results show a significant correlation between greasy hand and fibre diameter and a significant correlation between dust and greasy hand across the three INF sites. It is quite possible that wool wax and dust may interfere with the assessment of hand. Tables 5, 6 and 7 show the correlations for the individual sites, Kirby, Turretfield and Katanning respectively. For the number of samples assessed at each site, the Pearson's correlation coefficient R becomes significant at the 99.9% level for values of R greater than 0.22 (Kirby), 0.24 (Turretfield) and 0.23 (Katanning). At the 95% level values of R greater than 0.13 (Kirby) and 0.14 (Turretfield and Katanning) become significant. Greasy hand score was correlated with different traits at the different sites. Hand was most strongly correlated with RtC at Kirby, character at Turretfield and fibre diameter at Katanning (P<0.001). Interestingly, the correlation between dust and hand was highly significant for Kirby (P<0.001) and also significant for Katanning and Turretfield (P<0.05). Stevens (1994) also showed that large variations existed in correlations between subjective handle scores of raw wool and some other common objective and subjective wool characteristics.

Table 3: Correlation matrix for mean fibre diameter, curvature and RtC for the 2007 INF Merino drop (n = 1265)

	MFD	*MFC*
MFC	-0.18*	
RTC	0.28*	0.49*

* P<0.001

Table 4: Correlation matrix for hand score and various fibre parameters across all sites (n = 597)

	LAS_FD	*LAS_CURV*	*RTC*	*COL*	*CHAR*	*DUST*
LAS_CURV	-0.11					
RTC	0.24*	0.58*				
COL	0.04	0.17*	0.12			
CHAR	0.09	0.28*	0.29*	0.27*		
DUST	0.06	-0.19*	-0.08	-0.30*	-0.10	
HAND	0.42*	0.01	0.23*	0.03	0.12	0.32*

* P<0.001

Table 5: Correlation matrix for hand score and various fibre parameters for IN01- Kirby (n =214)

	LAS_FD	*LAS_CURV*	*RTC*	*COL*	*CHAR*	*DUST*
LAS_CURV	0.09					
RTC	0.34*	0.71*				
COL	0.18	-0.18	0.00			
CHAR	0.26*	0.29*	0.33*	0.28*		
DUST	0.22*	0.14	0.17	0.05	0.13	
HAND	0.29*	0.30*	0.42*	0.16	0.34*	0.35*

* P<0.001

Table 6: Correlation matrix for hand score and various fibre parameters for IN07- Turretfield (n = 181)

	MFD	*MFC*	*RTC*	*COL*	*CHAR*	*DUST*
MFC	0.02					
RTC	0.42*	0.47*				
COL	0.14	0.06	0.13			
CHAR	0.40*	0.23	0.43*	0.33*		
DUST	0.14	-0.16	-0.02	0.15	0.14	
HAND	0.33*	0.16	0.32*	0.33*	0.65*	0.21

* P<0.001

Table 7: Correlation matrix for hand score and various fibre parameters for IN08- Katanning (n = 202)

	MFD	*MFC*	*RTC*	*COL*	*CHAR*	*DUST*
MFC	0.03					
RTC	0.26*	0.49*				
COL	0.21	0.04	0.01			
CHAR	0.04	0.11	0.11	-0.02		
DUST	0.06	-0.08	-0.06	0.01	0.05	
HAND	0.53*	0.04	0.20	0.32*	0.03	0.16

* P<0.001

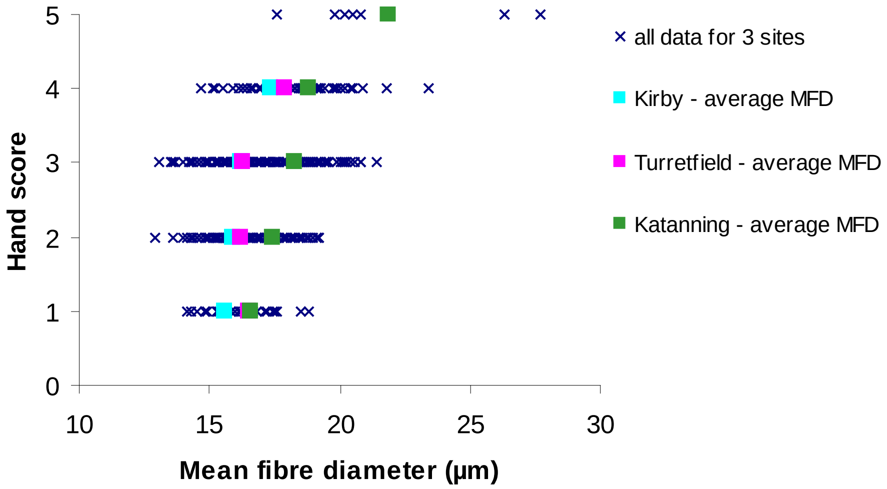

Figure 1: The relationship between mean fibre diameter (µm) and hand score. Also included is the average MFD for each Hand score for each of the sites

Genetic analysis of INF flocks

Hatcher (2010) estimated the heritability of handle and examined the sire breeding values and the phenotypic and genetic correlations between subjective hand and the other visual and measured wool traits for the 2007 drop. Her findings for the phenotypic correlations between fibre diameter, curvature, RtC and handle were low and less than 0.41, the genetic correlations were larger for these parameters except for fibre curvature and the heritability estimate for handle was 0.86. The estimated breeding value for handle for 32 sires ranged from -1.04 to 0.86.

Selection of fleeces for further subjective and objective analysis

RtC, MFC and MFD are highly correlated with each other, in particular MFC and RtC (Table 3). Pairs of samples were selected so that each pair were from the same flock and had similar mean fibre diameter and curvature as measured by Laserscan but different compression behaviour, nominally high and low RtC. It is expected that these samples should show differences in softness in loose wool form with overwhelming influence of diameter and curvature on hand removed by sample selection.

Figures 2 and 3 show the relationships between mean fibre diameter (Laserscan) and resistance to compression (RtC) and curvature, respectively, for all of the 2007 Merino progeny (n=1265). Diameter groupings exhibiting a range of RtC have been identified, namely 13.5 to 13.7 µm, 15.7 to 16 µm, 16.7 to 17 µm, 17.7 to 18 µm and 18.6 to 18.9 µm as shown in Figure 4.

From the relationships in Figure 4, 8 samples comprising of 4 matched pairs (2 each from Katanning, Kirby, Cowra and Turretfield) were selected for further felting and subjective testing. Test results extracted from the CRC database for the selected samples listed are in Table 8. To confirm the database and actual samples match, diameter and curvature of the selected samples were measured on the CSIRO Sirolan Laserscan and theses results are also given in Table 8. Although the mean fibre diameter measured by the two Laserscan instruments were not significantly different ($P > 0.05$), a sample from Katanning measured more than a micron greater on the CSIRO Laserscan than the value recorded in the database. A repeat test on the CSIRO Laserscan confirmed the larger diameter value (Table 8, data in brackets). The curvatures measured using the CSIRO Laserscan were greater in magnitude than those recorded in the database, because they were measured in an iso-propanol / water solution, whilst the database samples were measured at AWTA on a water-only Laserscan, in which swelling causes the fibres to decrimp leading to a reduced curvature.

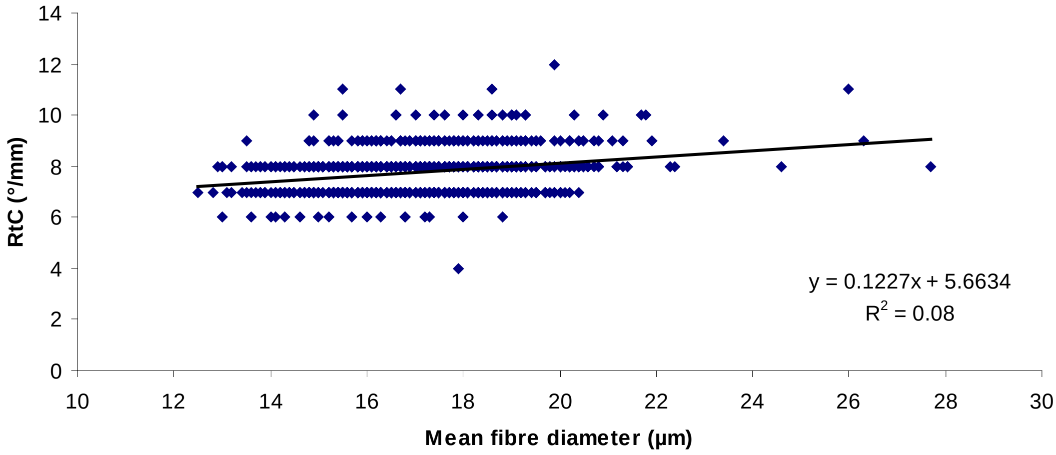

Figure 2: Spread of diameter and resistance to compression across the 2007 Merino progeny

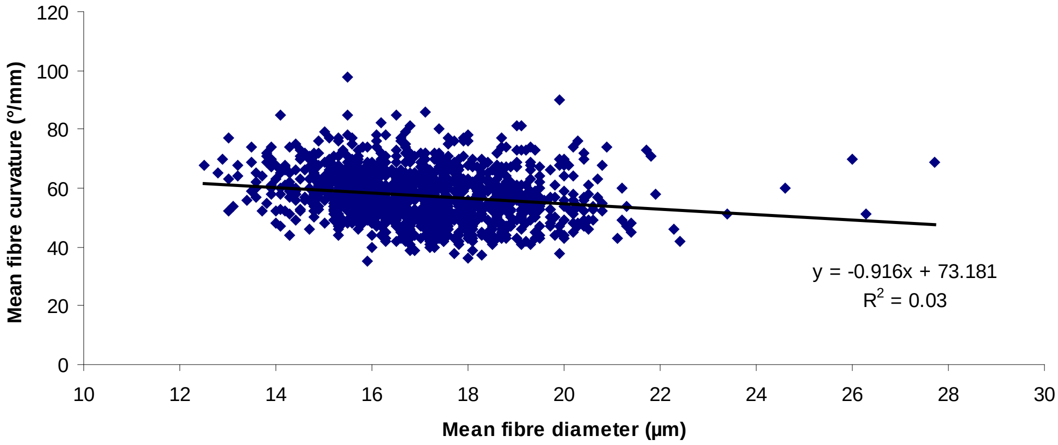

Figure 3: Spread of mean fibre curvature across the 2007 Merino progeny

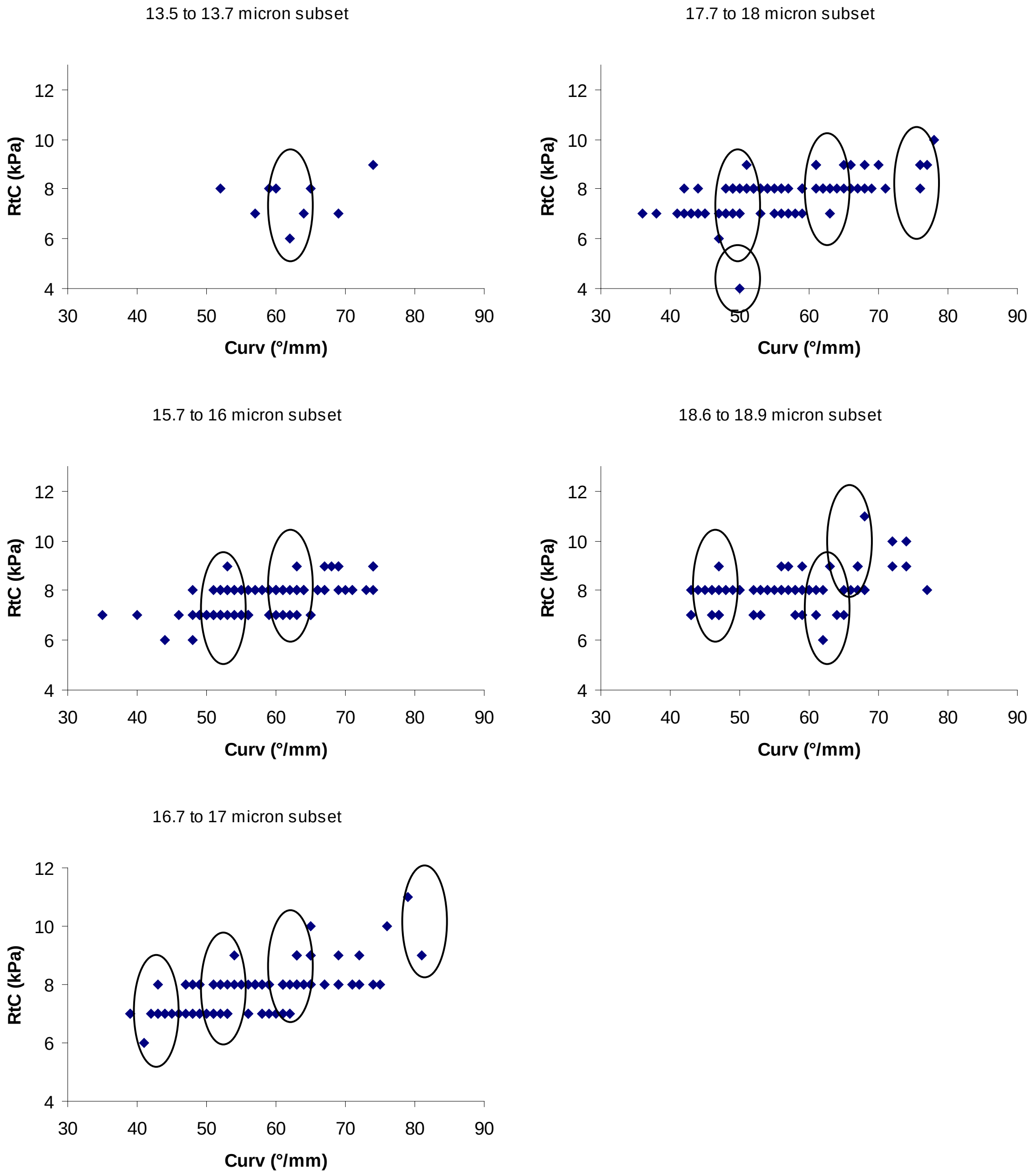

Figure 4: Relationship between fibre curvature and RtC for the various diameter slices

Table 8: Properties of selected INF mid-side samples obtained from the CRC database. Data in brackets represent the CSIRO Laserscan results.

Site	MFD µm	CVD %	MFC °/mm	RTC kPa	COL score	CHAR score	DUST score	HAND score
Turretfield	15.8 (15.9)	24.1 (23.1)	65 (101)	7	1	1	3	3
	15.8 (15.2)	29.8 (27.2)	63 (102)	9	2	3	3	3
Kirby	16.8 (16.7)	14.3 (14.3)	81 (119)	9	4	4	2	3
	16.7 (16.7)	20.4 (18.7)	79 (116)	11	3	4	3	4
Katanning	17.9 (19.2,19.1)	16.2 (16.1, 16.9)	50 (94,95)	4	1	1	4	3
	17.7 (17.4,17.6)	14.1 (14.1,16.3)	50 (90,97)	8	2	2	2	2
Cowra	18.8 (19.5)	16.0 (15.5)	67 (95)	9	2	4	2	
	18.6 (18.6)	17.2 (18.4)	68 (115)	11	2	4	4	

Feltball shrinkage of selected INF fleeces

The Aachen felting test I.W.T.O-20-69(E) was developed to measure the feltability of loose wool, particularly greasy wool before scouring as a method of anticipating undesirable felting in scouring and for the evaluation of shrink-resist treatments on tops (Blankenburg, 1969). Since the Aachen felting test instrument was not available at CSIRO, the felting method was modified by using a Mathis Labomat dyeing machine to agitate samples. A single lot of greasy wool was used to develop the method which is described in a CRC task report (Hillbrick et al., 2009). The variation between feltball diameters for this sample was low and it was established that only three test specimens were required for the estimate of mean feltball size to be accurate to within 0.5mm with 95% confidence.

The Labomat method was used to determine the felting propensity of the selected pairs of INF samples. However instead using three test specimens per sample, six specimens per sample were used. The feltball test results are illustrated in Figure 5. A large sample variance was observed for the Turretfield samples, suggesting that three test specimens per sample was not enough to ensure the mean feltball size is accurate to within 0.5mm with 95% confidence. Excluding the Turretfield samples, the average variation in feltball diameter obtained for the remaining INF samples was 0.57. Hence taking the mean of five feltball specimens per sample was sufficient to estimate the mean feltball size with 95% confidence.

The felting propensity of one sample from Katanning was significantly greater than all other samples ($P<0.05$). This sample had a low fibre curvature (50°/mm) and an RtC of 8 kPa. There were no significant differences between the felting properties of the other pairs with curvatures above 65°/mm.

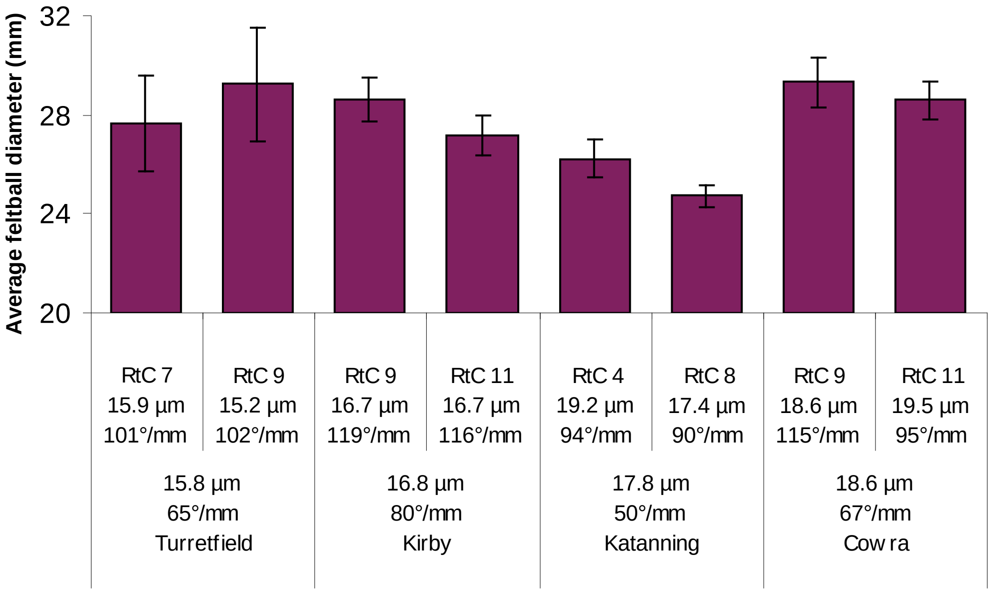

Figure 5: Felting propensity of selected INF wool samples using the Labomat feltball test

Subjective handle of degreased wools

Samples from Turretfield, Kirby and Katanning all had an existing greasy hand scores and were used for further subjective testing. The samples were solvent cleaned prior to subjective testing. The Soxtherm extraction in dichloromethane removed the solvent extractable wool wax and some of the dust from the wool sample. The amount of solvent extractable matter and dirt that was extracted from each sample was expressed as a percentage of the greasy weight of the wool and the results are listed in Table 9. The samples from Turretfield were the dustiest of the eight samples (Ave. 8% dust c.f. 5% for others). There was no significant correlation between the dust removed and the on-farm subjective dust score. An example of the level of dust and grease that was removed from a Turretfield sample by the Soxtherm extraction is shown in Figure 6.

Table 9: Solvent extractable material from the selected INF samples

Site	MFD µm	RTC kPa	Solvent extractables (% o.g.w)	Dirt (% o.g.w)	Dust Score (Database) (1 - 5)
Turretfield	15.8 (15.9)	7	10.03	9.53	3
	15.8 (15.2)	9	13.03	7.27	3
Kirby	16.8 (16.7)	9	11.86	3.81	2
	16.7 (16.7)	11	12.42	4.58	3
Katanning	17.9 (19.2,19.1)	4	7.06	3.54	4
	17.7 (17.4,17.6)	8	10.49	3.78	2
Cowra	18.8 (19.5)	9	10.06	6.33	2
	18.6 (18.6)	11	8.70	4.81	4

Figure 6: Turretfield mid-side sample before solvent scouring (left) and after a dichoromethane Soxtherm solvent extraction

All 15 possible pairs of the six samples were evaluated by ten judges and the results were analysed using a Friedman Ranked Sum analysis (Meilgaard et al., 1987). The rank sum for each sample was calculated by summing the ranks over all combinations and judges and represents the relative softness of samples in a series. The rank sum placed the samples in order of degree of softness, with a higher rank sum corresponding to a higher degree of softness. Table 11 summarises the softness ranking of the six samples. The critical value of

$T_{\alpha=0.05}$ was 11.1 and the calculated test statistic, Friedman's T was 66. The null hypothesis that all samples have similar softness was rejected and the Friedman's test statistic confirmed that at least some of the differences in rank sum were statistically significant. Tukey's HSD (honestly significant difference) multiple comparison procedure (Meilgaard et al., 1987) was used to compare the rank sums. The HSD $_{\alpha=0.05}$ was 22.1.

The difference in the rank sum of the two softest samples Turretfield (rank sum 181) and Katanning (rank sum 158) was larger than the HSD. Hence the Turretfield sample (rank sum 181) was significantly softer than all other samples.

Table 11: Softness of the selected INF samples after solvent scouring in the Soxtherm

(HSD $_{\alpha 0,05}$ = 22.1 within the series)

Softness Rank	Site	Rank sum (solvent scoured wool)	MFD (µm)	MFC (°/mm)	RTC (kPa)	Greasy hand score (1 - 5)
1	Turretfield	181	15.8 (15.9)	65 (101)	7	3
2	Katanning	158	17.9 (19.2,19.1)	50 (94,95)	4	3
3	Turretfield	157	15.8 (15.2)	63 (102)	9	3
4	Kirby	145	16.8 (16.7)	81 (119)	9	3
5	Katanning	134	17.7 (17.4,17.6)	50 (90,97)	8	2
6	Kirby	125	16.7 (16.7)	79 (116)	11	4

Interestingly the Turretfield sample that was ranked the softest (softness rank 1) of the solvent scoured wools did not have the softest hand score when assessed on farm in the raw/greasy state. The dust content of this sample was high (Table 9) which may have affected the greasy wool softness. Similarly, the Katanning sample with a greasy hand score of 2 was judged to be harsher (softness rank 5) than most of the other samples after the solvent cleaning process. The dust content of this sample was low, but in comparison to the other Katanning sample, it had a high grease content which may have affected the greasy hand assessment (Table 9). It was also noted that this Katanning sample compacted easily and formed large clumps during the subjective testing of the solvent cleaned sample. The lumpiness of the sample may have adversely affected the subjective softness assessment. Should this trial be repeated, the suggestion is that a fresh sample be used for each judge.

For the selected samples, the correlation between the greasy hand score and the hand of the solvent cleaned samples was not significant (P=0.79).

Why is there a significant difference in the softness of hand between the Turretfield Samples, even though they have similar fibre diameter and curvature?

This aim of this section is to identify secondary fibre properties that may influence the softness of loose wool. The two Turretfield samples were chosen because their softness is significantly different (when assessment is made on clean wool as discussed above) and their RtC is different even though they have similar fibre diameter and curvature. For identification purposes in the following discussion, the softest Turretfield sample (rank sum 181) is referred to as ‘soft handle’ and the least soft Turretfield sample (rank sum 157) is referred to as ‘harsh handle’. Individual fibres extracted from the ‘soft’ and ‘harsh’ handling Turretfield samples were subjected to detailed investigations of their shape, frictional and surface properties.

Fibre ellipticity

It is well known that the cross-sections of wool fibres are not circular, and ellipticity is an appropriate measure of the fibre non-circularity. Merino and non-medullated crossbred wools from Australia and New Zealand have mean ellipticity in the range of 1.18 to 1.25 and medullated wools can have ellipticity values up to 1.54 (Onions, 1962). A search of the literature revealed that the finest fibres used for ellipticity studies were approximately 18µm. Blankenburg et al. (1992) measured the ellipticity of fibres extracted from six (6) Interwoollabs 91/92 calibration tops ranging in nominal fibre diameter from 18µm to 36µm. They mounted the fibres in heat shrink tubing and cut cross-sections perpendicular to the fibre axis. Using this technique they found that average ellipticity values ranged from 1.17 for the 22µm top to 1.28 for the 36µm top. They observed a significant positive correlation between the fibre ellipticity and the mean fibre diameter. This is contrary to the findings of Anderson and Benson (1953) who also studied cross-sections of fibres of similar diameter to those tested by Blankenburg. They did not find a significant correlation between mean fibre diameter and fibre ellipticity.

The Single Fibre Analyser or SIFAN 3 developed by BSC Electronics Pty Ltd., WA, is a purpose built, commercial instrument that is able to measure fibre diameter at any number of different orientations by rotating the upper and lower jaws. Wang (2007) obtained a value of fibre ellipticity by averaging the two orthogonal diameter ratios obtained from four orientations and since these orientations were not necessarily at the major and minor axes, they reported a lower than expected ellipticity for wool (1.08 ±0.01). The SIFAN 3 was not used to estimate the ellipticity of the Turretfield samples because previous work has identified issues with the fibre alignment when the ellipticity of calibration wires were estimated (Hillbrick and Huson, 2009).

The fibre ellipticity of the Turretfield samples was estimated from the length ratios of the major and minor axes of transverse cross-sections of fibres that were embedded in Spurr’s firm resin. The ellipticity was measured on approximately 20 randomly selected fibres from each sample. A typical example of the variability in fibre ellipticity is shown in Figure 8 for the soft Turretfield sample. Table 12 summarises the descriptive statistics for the ellipticity values obtained for the soft and harsh Turretfield samples. The mean ellipticity values of 1.16 and 1.18 were not significantly different at the 95% level (P = 0.51).

Table 12: Mean ellipticity single fibres randomly selected from the soft and harsh handle Turretfield samples

	soft	*harsh*
Mean Ellipticity	1.16	1.18
Sample Variance	0.01	0.01
Minimum	1.07	1.04
Maximum	1.37	1.40
Sum	24.36	29.47
Count	21	25
Confidence Level (95.0%)	0.04	0.04

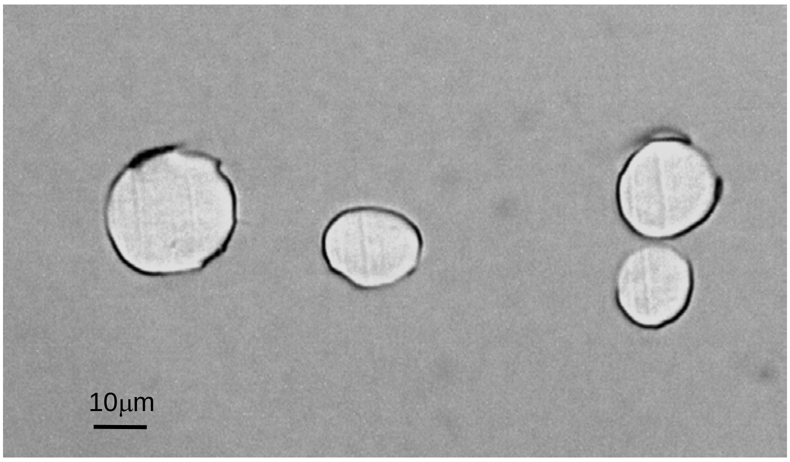

Figure 8: Variation in fibre ellipticity shown in transverse cross-sections of four fibres from the 'soft' Turretfield sample

Bending stiffness

Ellipticity and Young's tensile modulus are important for the calculation of bending stiffness as shown by equation 1. Our earlier study (Hillbrick and Huson, 2008) showed that tensile stiffness (Young's modulus) and RtC (softness) were not significantly related and that tensile modulus of wool was dependant on the diameter of the wool fibre. In this present study both samples have the same nominal fibre diameter, 15.5µm and curvature, 101°mm^{-1}. Hence it is assumed that the Young's modulus is the same for both samples, and since the ellipticity is also the same, the bending stiffness of both samples is equal. The conformation of the Young's modulus of these specific samples will be completed and reported as an addendum to this report.

These results suggest that differences in the handle observed between the pair of 15.5µm samples with a curvature of 101°mm-1 was not due to differences in the bending stiffness of the samples.

Single Fibre Friction

Table 13 summarises the results for the fibre to metal frictional properties of the soft and harsh Turretfield samples. Single fibre friction was measured in both the root to tip (with-scale) and tip to root (against-scale) directions by the capstan method described in the experimental section. As expected the coefficient of friction was significantly higher for the against scale direction than the with scale direction for both samples ($P<0.01$). The directional frictional effect (DFE), which is the difference in the between the against-scale and with-scale coefficients of friction, was not significantly different for the samples ($P=0.52$). Surprisingly the softer handling Turretfield sample had a significantly larger coefficient of friction regardless of the direction of rubbing ($P<0.05$).

Interestingly Wortmann and Schwan-Jonczyk (2006) found significant differences in the frictional forces of hair samples that had the same fine fibre diameter, ellipticity and handle. They speculated that in their example surface friction played a minor role in the softness of hand.

Friction is a complicated measure involving the normal force between the two surfaces, the nature of the two surfaces and the area of contact between them. Different scale structures are likely to lead to different amounts of contact between two surfaces and hence different friction. For example a higher scale frequency is likely to lead to an increase in surface contact and hence higher friction. The presence of scales on a fibre will initially decrease the contact area which, for contact between the fibre and a smooth surface such as our metal capstan, could result in a decrease in friction. Fibre to fibre friction on the other hand would be expected to increase in the presence of scale edges.

Our results suggest that the increased friction observed for the fibres from the soft handling sample is due to an increase in contact area between the fibre cuticle and the capstan. The surface properties of the cuticle are explored further in the following section.

Table 13: Fibre to metal coefficients of friction for the soft and harsh Turretfield Samples in both the with scale and against scale directions

	Soft		Harsh	
	against scale	with scale	against scale	with scale
Mean single fibre coefficient of friction (μ)	0.31	0.27	0.28	0.23
Standard Error	0.01	0.01	0.01	0.01
Standard Deviation	0.05	0.04	0.04	0.03
Sample Variance	0.002	0.001	0.001	0.001
Minimum	0.22	0.20	0.21	0.18
Maximum	0.39	0.36	0.37	0.31
Count	20	20	20	20
Confidence Level (95.0%)	0.02	0.02	0.02	0.01
CV %	15.13	14.08	12.81	12.09

Surface properties – cuticle step height, scale frequency and scale roughness

Much of the work on cuticle scale height and scale frequency has been conducted using a scanning electron microscope (SEM) in an effort to differentiate between wool and specialty fibres (Wortmann and Arns, 1986, Wortmann et al., 1989, Wortmann, 1991, Wortmann and Wortmann, 1992, Wortmann et al., 2003a, Wortmann et al., 2003b, Wortmann and Augustin, 2004, Wortmann and Phan, 1999). International Wool Textile Research Organisation (IWTO) Test method 58 embodies this work (IWTO, 2001). Fibres are identified by the height of the distal edges of the cuticle scales (not false scale edges or shoulders). Scale height ≥ 0.55 µm is indicative of wool, whilst scale height < 0.55 µm is indicative of speciality fibre. More recently Varley (2006) modified the SEM technique by bending fibres through 180º and found a greater overlap in the scale height properties of wool and cashmere than reported by Wortmann and Arns (1986).

Scanning probe microscopy (SPM) is an ideal technique for non-invasive examination of the surface of wool fibres. It is used to image the surface of wool fibres with nanometer resolution by scanning a fine tip over the surface and monitoring the position of the tip (Huson et al., 2008). It has advantages over SEM because it does not require a vacuum or conductive coating of the sample before imaging and samples can be imaged dry, in water or at any relative humidity. A true 3D image is generated allowing SPM to provide quantitative information on the surface topography of fibres such as cuticle step height, length and roughness. The term cuticle step height is used in place of scale height because our method measures numerous consecutive scale edges and no distinction is made between true scale edges, false edges or shoulders.

Making measurements such as height and roughness on a curved surface requires care. It is normal to flatten the surface using a mathematical algorithm however in the case of scale height as we move away from the centre of the fibre errors are introduced. For cuticle step height and frequency measurements therefore we have chosen to image with a 4:1 aspect ratio which allows us to capture a 60 μm x 15 μm image incorporating 5-6 consecutive scale edges and only analyse the central 5μm of each image. Figure 10 shows a SPM height map obtained for the harsh handling Turretfield sample. The corresponding cross-sectional plot shows variation in the cuticle step heights along the 60µm region. Scale roughness was determined by scanning a 5 µm x 5 µm area, avoiding scale edges.

Table 14 summarises the SPM results for cuticle step height, length and roughness of the soft and harsh Turretfield samples. Figure 11 shows a histogram of the cuticle step heights. Although a wide distribution in step height was found, the soft handling Turretfield sample has a significantly lower cuticle step height than the harsher handling sample (P<0.001). There is no significant difference in the scale length (scale frequency) between the soft and harsh Turretfield samples (P=0.07). The cuticle surface between the scale edges was rougher for the harsher handling sample (P=0.04). This increased surface roughness may reduce the contact between the fibre and the capstan during friction testing, leading to the reduction in friction as was observed in the previous section. Differences in the mechanical properties of the cuticles could also lead to differences in contact area and hence friction. This will be explored further using the SPM to make nanomechanical measurements.

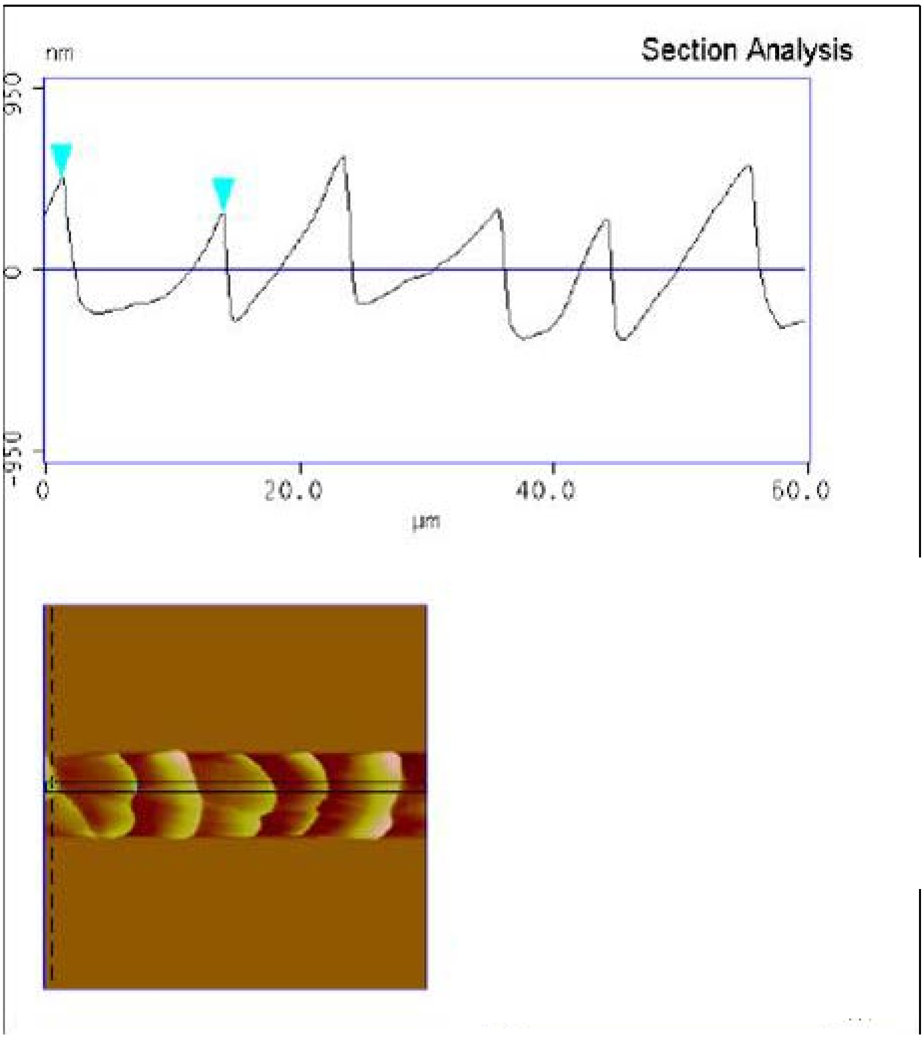

Figure 10: Scanning probe microscope ‘section’ image of Sample 8, for scale length determination

	Soft handle - scale properties			Harsh handle - scale properties		
	height (nm)	*length (nm)*	*roughness Rms Rq (nm)*	*height* (nm)	*length (nm)*	*roughness Rms Rq (nm)*
Mean	452.60	9.77	6.82	598.14	9.25	8.03
Standard Error	11.21	0.22	0.31	14.34	0.19	0.49
Standard Deviation	173.64	2.84	1.55	214.20	2.54	2.89
Minimum	102.31	3.52	4.89	80.45	3.75	4.20
Maximum	923.52	19.92	11.64	1411.00	18.75	15.69
Count	240	168	25	223	187	35
Confidence Level (95.0%)	22.08	0.43	0.64	28.27	0.37	0.99

Table 14: Scale properties of soft and harsh Turretfield samples measured on a Scanning Probe Microscope

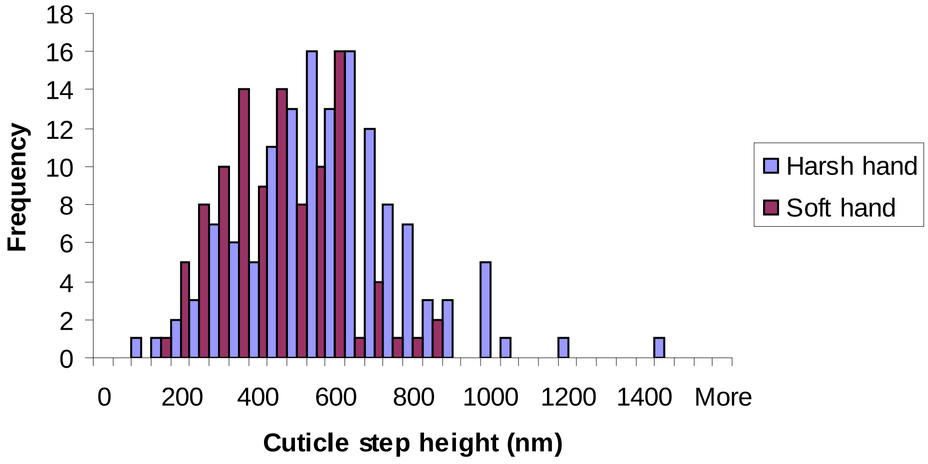

Figure 11: Histogram showing the cuticle step height distribution of the soft and harsh hand Turretfield samples

Conclusion

The correlation coefficients between RtC and curvature, and RtC and diameter for the Information Nucleus flock (2008 shearing/2007 drop) were 0.49 and 0.28 respectively. These results are in good agreement with values reported in the literature. Greasy hand was correlated with both fibre diameter and dust. Greasy hand was most strongly correlated with RtC at Kirby, character at Turretfield and fibre diameter at Katanning.

For the limited samples studied, no correlation between the hand of greasy and solvent cleaned wool was observed. Similarly no relationship between feltball diameter and softness of hand could be established.

Results suggest that differences in the handle detected between the pair of 15.5µm samples with a curvature of 101°mm^{-1} was related to differences in the cuticle step height and roughness characteristics of the fibres and not the bending stiffness. Fibres from the soft handling sample had a lower cuticle step height and a smoother surface. The high coefficient of friction recorded for this sample may be attributed to an increased surface contact area.

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