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Mechanical characterization of surface wrinkling properties in fibrous sheet materials by facile folding process

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A R T I C L E I N F O

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A B S T R A C T

Wrinkling and folding are crucial morphological and structural motifs in polymeric sheet materials. In this study, a simultaneous-mechanical test method was proposed to evaluate the wrinkling behaviour by simply constructing the folding deformations of fibrous sheet materials. The internal relationship between fabric folding and wrinkling was studied, and the similar power law relation of the wrinkling force and the number of folded layers between wrinkling and folding of fabrics was experimentally proved. This leads to a view of wrinkling from a hierarchical folding process, laying down the way to describe the disordered wrinkling by a facile folding test. The proposed test method and instrument can simulate the complex deformation and mechanical action during the wrinkling process by curve parameters extracted from the measured force-displacement curve. The correlation analysis between the curve parameters and wrinkling grades of subjective evaluation was conducted. Moreover, the prediction model of wrinkling grades was constructed and validated to give a direct overall evaluation of wrinkling grades for industrial application. The evaluation results of the prediction model based on the proposed mechanical test method showed good agreement with the traditional subjective evaluation results, which indicated that the designed method and instrument provided a feasible and effective measurement using a facile folding process for the surface wrinkling properties of fibrous sheet materials, enhancing our design and tuning capability for the morphology instability and wrinkling of fibrous sheet materials.

1. Introduction

Wrinkling or folding phenomena arise naturally in multitudinous circumstances, from deformations and physical self-avoidance of flexible sheet materials to formation of protein and tissues of living organisms. Despite generally easy to state, the wrinkling degree is difficult to quantify. Fabrics, as a typical fibrous sheet material with low elastic moduli, are especially susceptible to various mechanical actions to form wrinkles and creases in the manufacturing process and daily application, which directly affects the performance and market value of textile materials [1]. The tendency of fabrics to wrinkle or crease is associated with "ease-to-care" properties (*e.g.*, durable press, non-ironing after washing, anti-wrinkle, machine-washable behaviours), and can determine consumers' judgement on fabric quality and aesthetic appearance during purchasing process [2]. On the other hand, the understanding of physics and characteristics of wrinkles in textile materials can facilitate the design and fabrication of tunable pleats and patterns of fabrics, and enhance the stability of textile-based flexible electronics in emerging applications [3,4]. Therefore, the characterization and regulation of the surface wrinkling properties of textile sheet materials have become an urgent requirement in both the industrial manufacturing and novel product design [5–7].

The wrinkling property of textile materials has been evaluated by fabric's "smoothness appearance", which has long been used to describe the surface rugosities and chaotic morphological undulations of fabrics in textile and clothing industries. Generally, the fabric samples were treated first by standard washing or twisting and stirring process to form wrinkles on their surface, and then the wrinkled fabrics were compared with standard samples to rank the wrinkle level by subject perception. However, subjective visual evaluation is easily influenced by individual experience, showing low precision and poor reproducibility, as well as high labour cost and time cost.

In recent decades, a majority of scientific studies have shown intensive interest in the application of image processing and computer

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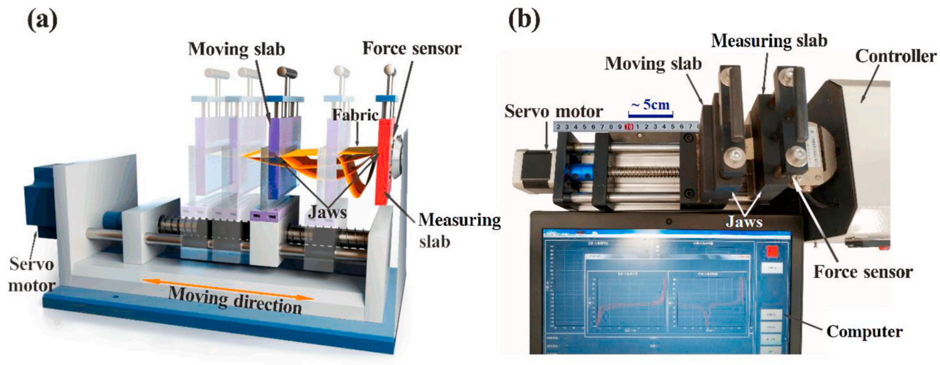


Fig. 1. (a) Apparatus design and (b) top view image of the fabric wrinkling evaluation system.

vision technology to surface wrinkle's assessment. The pioneered work has been done by Xu and Reed [8], and they developed an automatic grading system for fabric wrinkle recovery to quantify wrinkled appearance using two dimensional (2D) image method. In addition, Na and Pordeyhimi [9] found that fabric wrinkling could be reliably characterized using gray level and surface statistics, co-occurrence analysis, and power spectral density of image profiles. Choi et al. [10] developed a new instrument for fabric wrinkle grading based on the 2D Fast Fourier transform. In terms of three dimensional (3D) methods, Xu et al. [11] developed a new surface profiler to evaluate the smooth appearance of fabrics by using laser triangulation and image processing techniques. Later, Su and Xu [12] improved this laser triangulation method by using a multiple line generator for profile scanning and an artificial neural network for data classification, which improved the efficiency and accuracy. Yu et al. [13] proposed a stereo vision system for reconstructing the 3D surface of a wrinkled fabric and for detecting and characterizing wrinkles to evaluate the severity of wrinkling. Yang and Huang [14] reconstructed the 3D surface of wrinkled fabrics using a photometric stereo method, and characterized the wrinkle degree by roughness, fractal dimension, surface area and average offset. The image technique has improved the objectivity of the characterization of fabric wrinkling properties; however, the image method is essentially a visual evaluation approach in principle, and is highly challenging since:

i Extracting the precise wrinkle features from fabric surface image is difficult because of the diversity and complexity of textile materials in color and texture;
ii Chaotic washing and pretreating process for preparing the wrinkled fabrics results in inconsistent testing conditions, intensifying the low repeatability of the measurement results;
iii Interpreting the intrinsic factors that cause fabric wrinkles is challenging by image-based appearance evaluation, calling for an innovation in the physico-mechanical testing method.

Recent studies have provided insight into the connection between fabric wrinkling and the inherent physical and mechanical properties of fabrics [15–19], laying down the basis of using mechanical testing to characterize wrinkling of textiles. Various mechanical loads may cause complex deformation of textile materials and further trigger wrinkles analogous to multiple folds induced by buckling/bending and compression. Some effort has attempted to characterize the wrinkling of flexible materials by mechanical indices. Pan [20] used the area difference of the pushing-force – displacement curves between a smooth fabric and the corresponding wrinkled fabric to evaluate fabric's wrinkle recovery ability. On this basis, Sun et al. [21] extracted several mechanical indices to analyse the wrinkling of fabrics by a double-extraction method. However, early works only focused on directly capturing the mechanical variables induced by the random wrinkling of materials, which makes it difficult to physically interpret the mechanical indices due to the complex and stochastic deformation of fabric samples during testing. More applicative approaches to characterizing the wrinkling properties of fibrous sheet materials are required to overcome the obstacles described above.

Therefore, this paper presents a facile, novel mechanical testing method named the fabric wrinkling evaluation system (FWES), which utilizes a simultaneous mechanical test to construct folding-centric multiple deformations of samples, achieving a combination of temporal and spatial resolution in the measurement of viscoelastic textile materials. The internal relationship between regular folding and random wrinkling was studied. It was intriguing to see that the wrinkling force increased as a power law with the number of folded layers, and the exponent of the folding and wrinkling process of fabrics was roughly the same. The correlation analysis was conducted to explain the internal relation between the mechanical characteristic indices and the fabric wrinkling response. The prediction model for characterizing the fabric surface wrinkling performance was constructed by stepwise regression analysis, and reliability of the predicted results from the model was verified by a group of independent experiments. This work is able to foster new ideas of using folding features to predict the wrinkling behaviours of textiles and pioneering mechanical tests as instrumental method to evaluating the surface wrinkling levels of fibrous sheet materials.

2. Apparatus design and testing principle

As shown in Fig. 1, the FWES mainly comprises measurement component, transmission component and corresponding data acquisition and processing system [22]. The measurement component includes a moving slab, a measuring slab and a force sensor with the measuring range of −500–500 cN and accuracy of 0.01%F.S. A pair of jaws is embedded into the moving slab and measuring slab with a 45° bevel to ensure the buckling stability of fabrics during test. The transmission component is driven by a servo motor, and the data collection and processing system consists of a controller and a computer with an analysis software package.

The servo motor controls the moving slab to achieve a reciprocating action relative to the measuring slab, constructing multiple deformation of the measured fabric. At the same time, the force sensor collects the analogue signals induced from mechanical response of the fabric in real time and outputs the force-displacement test curve on the control panel by the computer.

Textile materials are generally viscoelastic and show strong time dependence in their physical behaviours. The FWES provides a simultaneous measurement with an acceptable temporal and spatial resolution, not only overcoming the main drawbacks of the prevailing visual methods to evaluating wrinkle property of fabrics with complex textures and colours, but also helping us to understand the dynamics of the whole wrinkling process with an enhanced accuracy of measurement.

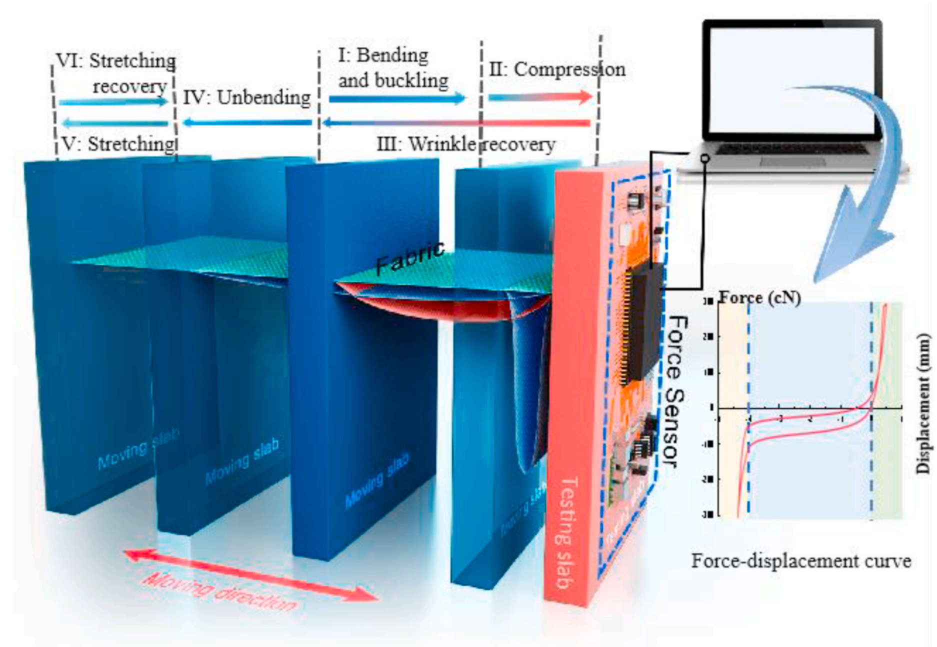


Fig. 2. Illustration of the simultaneous testing process and the main measurement stages of the fabric wrinkling evaluation system.

Table 1
Primary parameters of samples.

Sample No.	Thickness (mm)	Weight (g/m^2)	Young's modulus (N/tex)	Structure	Composition
1#	0.212	115.4	2.98	Plain	Polyester/ cotton
2#	0.290	110.8	2.40	Plain	Cotton
3#	0.228	155.4	3.42	Twill	Cotton
4#	0.216	121.5	2.38	Plain	Cotton/nylon
5#	0.232	119.6	1.89	Twill	Cotton/ nylon/ spandex
6#	0.475	186.2	3.18	Plain	Cotton/ polyester/flax

According to the typical deformation features of the fabric, the simultaneous testing process can be divided into six testing stages, namely, (I) the buckling and bending, (II) compression, (III) wrinkle recovery, (IV) unbending, (V) stretching and (VI) stretching recovery, as shown in Fig. 2. In carrying out a test cycle, the servo motor drives the moving slab by transmission component to move towards the measuring slab, and the fabric starts to fold between the measuring slab and the moving slab, forming the flexural buckling deformation of the fabric. The moving slab continues to approach the measuring slab until the two wings of the fabric contact each other, and the folded fabric is compressed. When the force sensor detects that the force on the fabric reaches the set value of the maximum compression force, the moving slab stops, followed by a certain compression stagnation time to enhance the crease of the fabric. The moving slab then moves in reverse, gradually restoring the deformation of the folded fabric until the moving slab returns to the origin. The moving slab continues to move in reverse, and the fabric is unbent and stretched, which ends with a designed tension. Finally, the moving slab moves closer to the measuring slab to conduct the stretching recovery test. Meanwhile, the mechanical response of fabric deformation is monitored by a force sensor and the corresponding force-displacement curve can be obtained to characterize the fabric's surface wrinkling.

3. Analysis of folding and wrinkling

Folding and wrinkling of fibrous sheet materials are considered two distinct deformation modes, namely, the former is regular and deterministic, while the latter is random and disordered; however, previous studies of printing paper have shown that the stiffness generating from folding and crumpling process has the same nature [23–25]. This implies that the mechanical signal acquired from folding and wrinkling process can reflect similar physical features of fabrics, laying down the way to describe the random wrinkling by a folding test. Here, the relation between the folding and wrinkling is experimentally examined by a set of fabric samples, as shown in Table 1.

Table 2
Summary of mechanical response of folding fabrics.

Folding layers	1#		2#		3#		4#		5#		6#	
	F/E	T/D	F/E	T/D	F/E	T/D	F/E	T/D	F/E	T/D	F/E	T/D
1	0.56	0.03	1.06	0.04	0.87	0.03	0.55	0.03	0.33	0.03	1.46	0.06
2	1.03	0.06	1.44	0.08	1.76	0.06	1.08	0.06	0.84	0.06	2.11	0.13
3	1.53	0.09	2.58	0.12	3.63	0.09	1.63	0.09	1.07	0.09	3.72	0.19
4	2.77	0.11	3.87	0.16	4.96	0.12	1.90	0.12	1.95	0.12	5.33	0.25
5	3.55	0.14	5.74	0.19	5.73	0.15	2.70	0.14	2.55	0.16	7.24	0.32
6	3.97	0.17	6.65	0.23	6.52	0.18	3.00	0.17	2.76	0.19	8.53	0.38
7	4.39	0.20	9.00	0.27	10.03	0.21	3.74	0.20	3.18	0.22	10.27	0.44
8	5.20	0.23	9.58	0.31	10.34	0.24	4.34	0.23	3.92	0.25	13.65	0.51

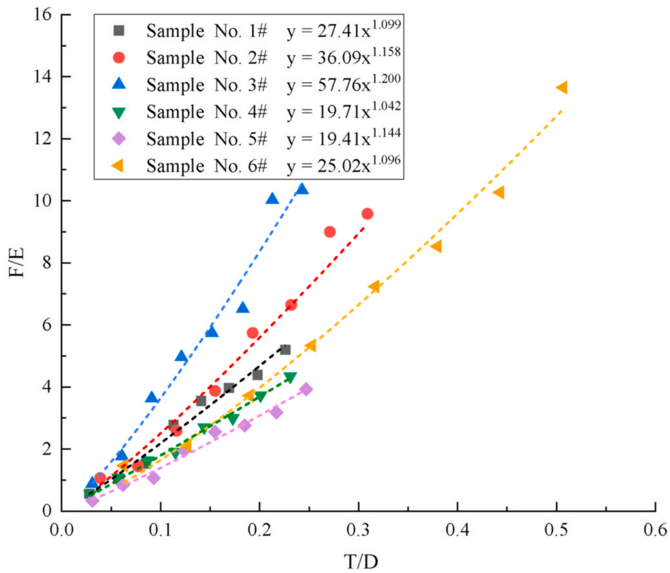


Fig. 3. The relationship between F/E and T/D in the folding process of 6 fabrics. Dotted line: power-law fitting.

3.1. Folding process

The relationship between the mechanical response and stacking thickness of fabric layers in the folding process was analysed here. Each fabric was cut into (1 + 2+3 + 4+5 + 6+7 + 8) × 3 = 96 samples with length × width of 40 mm × 20 mm for warp folding and weft folding tests, respectively. The FWES was used to test the force-displacement curve for folding deformation of fabrics whose thickness ranges from 1 (single fabric) to 8 layers (a stack of fabric). To eliminate the effect of different fabric properties on the physical rules, two parameters, i.e., F/E and T/D were introduced, where F is the average force value of the fabric per unit length during folding, E is the Young modulus, T is the total thickness of folding fabrics, and D is the horizontal distance between the two jaws. The testing results are summarised in Table 2.

Physically, the mechanical response of the measured fabrics with different stacking thickness is fitted by power law equation [25],

$$\frac{F}{E}=\alpha\left(\frac{T}{D}\right)^{\beta} \tag{1}$$

where α is a characteristic scale and β is the exponent of the power ratio. The stacking fabrics are considered a hierarchical structures, and the folding force increases with the increase of the stacking thickness, as shown in Fig. 3. The standardized folding forces$F/E$of the fabrics all show good agreement with the stacking parameter$T/D$by power law, as indicated by the high coefficient of determination $R^2 = 0.99$. The exponent of the power law divergence for all the measured fabrics is $\beta \approx 1.1$, (see Fig. 3), which may be induced by the interactions between layers of fabrics in the folding process. Thus the exponent reflects the general relation between folding force and hierarchical layers with energy dissipation.

3.2. Wrinkling process

To investigate the possible structure of wrinkled fabric in its original compact state and measure the corresponding forces in situ, we used a Bobo ball to wrinkle a fabric as a compact ball, and flexible pressure sensor is attached to the inner surface of Bobo ball to measure the wrinkling force (see Fig. 4(a)). Fabric samples with edge sizes of $L = 20$, 25, 30 and 35 cm were kneaded into Bobo balls with diameters R, forming five different compaction ratios $\phi = L/R$, that is, 4.55, 5, 5.45, 5.83 and 6.25 respectively. Three replicates were carried out for each sample, and the force value of each test was recorded at 5 min after

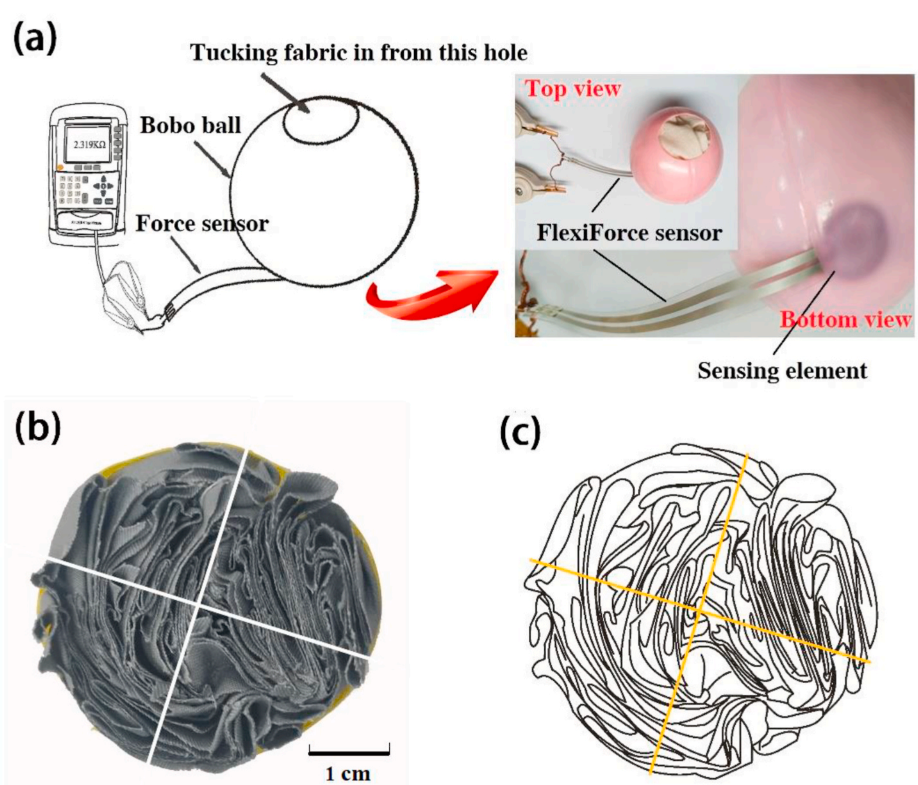


Fig. 4. (a) Schematic diagram and experimental setup for evaluating the wrinkling structure and force of fabrics, (b) Picture of a wrinkled cross section and two orthogonal directions used to extract the number of folded layers N and (c) Digital structure of wrinkled cross section of a fabric.

Table 3
Summary of mechanical response of fabric wrinkling.

Compaction ratio (L/R)	1#		2#		3#		4#		5#		6#	
	F/E	N	F/E	N	F/E	N	F/E	N	F/E	N	F/E	N
25/5.5 = 4.55	3.95	28	4.3	30	3.77	30	4.61	28	3.58	26	3.53	30
20/4 = 5	4.39	32	6.08	36	4.6	32	5.82	33	3.66	28	3.90	32
30/5.5 = 5.45	4.89	34	7.53	40	5.84	38	6.23	34	4.49	33	5.15	38
35/6 = 5.83	5.62	44	9.44	47	7.02	49	8.4	42	5.91	42	7.03	50
25/4 = 6.25	7.72	53	10.55	52	8.56	56	10.81	53	8.65	54	9.48	58

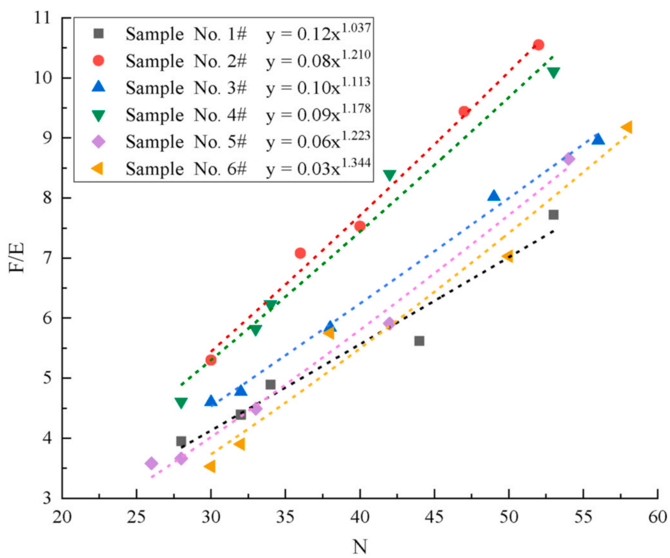


Fig. 5. The relationship between F/E and N in the wrinkling process of 6 fabrics with a power law.

compacting fabric into the Bobo ball. Moreover, a cross section was obtained by cutting the Bobo ball containing the wrinkled fabric in half along its diameter. In this section, the folding number N of the sample in the wrinkling configuration was measured in two orthogonal directions passing through the centre of the cross section (Fig. 4(b) and (c)). From the view of the cross section of cut wrinkled fabric, it can be deduced that the wrinkling is also a hierarchical process, which is similar to the repeated/stacked folding process. To further analyse the physical features of wrinkling, the values of the F/E and N are extracted from the experimental tests and are listed in Table 3. The relation between the two parameters$F/E$and N is fitted by power law in Fig. 5.

It can be seen from Fig. 5 that the wrinkling force increases with the increase of average number of wrinkling layers, showing similar trends with the folding process, and the force value is dependent on the compaction ratio and the number of layers (see Table 3). Integrating the fitting equations in Fig. 5, the relation between theF/E and N can be expressed by equation (2), similar to that of the folding process.

$$\frac{F}{E} \sim N^{\gamma} \quad (2)$$

The exponent $\gamma$is independent of the number of wrinkled layers, which is$\gamma \approx$1.2, slightly higher than the exponent $\beta \approx$ 1.1. This small difference may be caused by the fact that the interaction is more significant during the wrinkling process when a fabric is restricted in a Bobo ball compared with the situation where a fabric is just stacked during folding process. However, the folding and wrinkling processes still show a similar physical regulation with a power law relation. In other words, it can be considered that wrinkling and folding are very similar in nature, and the wrinkling process should be considered as deriving from continuous folding events. Physically, the regular folding test can capture the important features of disordered wrinkling.

Table 4
Primary parameters of 28 fabrics.

Sample No.	Thickness (mm)	Weight (g/m^2)	Bending rigidity (cN·cm^2·cm^{-1})	Structure	Composition
1	0.573	258.4	0.746	Plain	Cotton
2	0.398	170.7	0.385	Plain	Cotton
3	0.256	142.4	0.722	Plain	Cotton/ polyester
4	0.220	136.6	0.248	Plain	Cotton
5	0.432	184.8	0.170	Plain	Cotton
6	0.775	371.8	1.292	Twill	Cotton/ polyester
7	0.447	199.8	0.550	Twill	Cotton/ polyester
8	0.215	134.3	0.123	Plain	Polyester
9	0.273	111.1	0.076	Plain	Viscose
10	0.216	117.5	0.265	Plain	Viscose
11	0.226	124.7	0.683	Plain	Viscose
12	0.419	207.4	0.894	Plain	Cotton/ polyester
13	0.397	205.2	0.439	Twill	Cotton
14	0.228	155.4	0.369	Twill	Cotton
15	0.216	121.5	0.077	Plain	Cotton/ nylon
16	0.343	202.5	0.433	Twill	Cotton/ nylon/ spandex
17	0.333	200.6	1.036	Plain	Wool
18	0.225	114.5	0.062	Plain	Nylon
19	0.450	270.4	1.026	Twill	Cotton/ spandex
20	0.335	165.2	0.132	Twill	Cotton/ Viscose
21	0.335	165.3	0.392	Plain	Flax
22	1.660	575.0	2.583	Plain	Wool/ polyester
23	0.315	208.0	1.140	Twill	polyester/ nylon
24	0.260	116.5	0.093	Plain	Cotton
25	0.687	430.3	2.072	Twill	Wool
26	0.219	122.9	0.211	Plain	Cotton
27	0.232	119.6	0.153	Twill	Cotton/ nylon/ spandex
28	0.216	115.6	0.113	Plain	Cotton/ polyester

Therefore, the surface wrinkling characteristics of fibrous sheet materials can be characterized in virtue of the folding process.

4. Experimental protocol

4.1. Sample preparation

Twenty-eight commercial fabrics with different structure, composition and anti-wrinkle properties were collected. And all samples were conditioned at 20 ± 3 °C and relative humidity 65 ± 5% for at least 24 h before the test. The basic specifications of the samples are shown in Table 4.

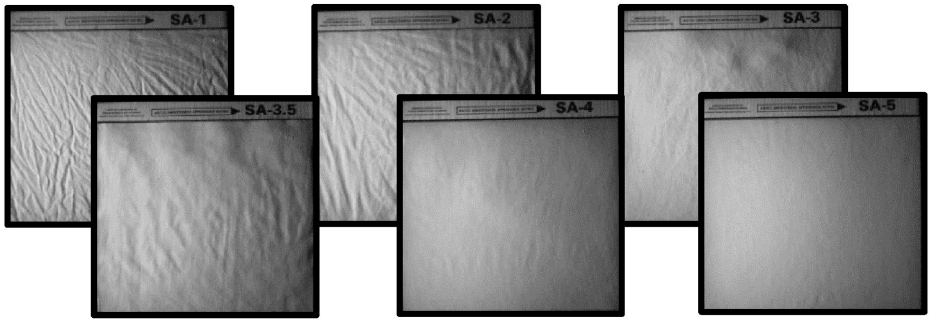


Fig. 6. AATCC standard photographs (SA-1~SA-5).

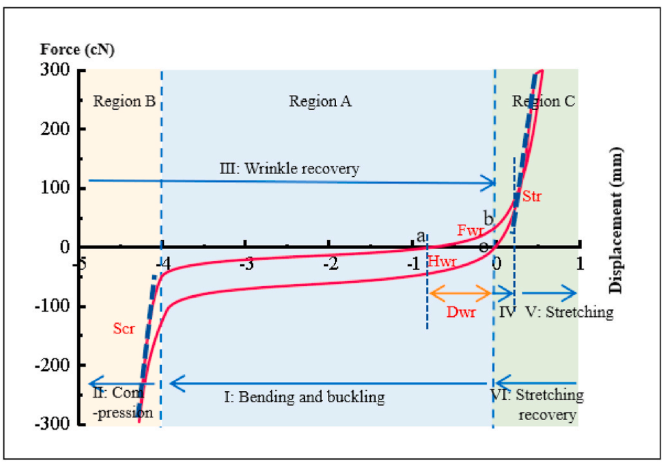


Fig. 7. The typical force–displacement curve of fabric and illustration of the curve parameters.

4.2. The FWES testing

The experimental parameters of the FWES were set as follows: the horizontal distance between the two jaws was 5 mm, the maximum compression force and the maximum tensile force were 300 cN, the stagnation time of the compression and stretching recovery of the moving slab was 30s, the movement speed of the moving plate was 20 mm/min, and the sampling frequency of the force value was 90Hz. Each fabric was tested by cutting three samples with the size of 40 mm × 20 mm for both warp and weft directions, and the average value of six curves was calculated as final test results.

4.3. Subjective evaluation of surface wrinkling

Referring to the American Association of Textile Chemists and Colorists (AATCC) test method 124-2011, the fabrics were cut to 380 mm × 380 mm for subjective evaluation. All the samples were first treated by standard washing and drying process, and then six judges assess the samples by comparing with a set of standard samples under the standard light source, ranking the wrinkling grade of the fabrics from 1 to 5. The AATCC 124-2011 standard samples are shown in Fig. 6, and the surface wrinkling grade of the fabrics is divided into six levels, namely SA-1, SA-2, SA-3, SA-3.5, SA-4 and SA-5, where the SA-1 indicates the strongest surface wrinkling, and the SA-5 represents the lightest wrinkling degree and the smoothest surface.

5. Characterizing surface wrinkling by folding mechanical parameters

5.1. Test curve analysis and feature parameter extraction

The typical force-displacement curve tested by the FWES is shown in Fig. 7. According to the multiple deformation characteristics of the sample, the test curve can be divided into three regions, namely, the bending and recovery region (region A), the compression and recovery region(region B) and the stretching and recovery region (region C).

The region A corresponds to the bending and buckling stage and wrinkle recovery stage of the test. In the wrinkle recovery stage, the absolute value of the force gradually decreases to zero (point a, see Fig. 7), and then the force value increases from zero, crossing the vertical axis at point b, to overcome the inherent bending force generated by the residual wrinkling of the fabric. Therefore, the deflection displacement *Dwr* between the point a and coordinate origin O, and the wrinkling residual force *Fwr*, namely the vertical coordinate of point b, can be extracted as the curve parameters of the wrinkle recovery performance of the fabric.

$$D_{wr} = \|\overrightarrow{ao}\| \tag{3}$$

$$F_{wr} = \left\|\overrightarrow{ob}\right\| \tag{4}$$

In addition, it is reported that the bending hysteresis of fabric is closely related to the wrinkle recovery characteristics [26], it can be expressed by scale law as follows [27]:

$$B_{hm} \sim W^n \tag{5}$$

where B_{hm} is bending hysteresis moment, *W* is wrinkle recovery angle and *n* is power-law exponent. Therefore, the hysteresis distance *Hwr* between the bending and buckling curve and the crease recovery curve at Point a can be extracted as a parameter to evaluate the fabric wrinkling.

$$H_{wr} = F(a)_{\max} - F(a)_{\min} \tag{6}$$

The region B corresponds to the compression stage and the initial stage of wrinkle recovery. After the compression test, the moving slab moves away from the measuring slab in reverse so that the compressed sample gradually recovers. In the initial stage of the wrinkle recovery of the sample, the force-displacement curve drops sharply, where the compression rebound slope *Scr* is extracted as a possible feature parameter to evaluate the fabric's smoothness appearance.

$$S_{cr} = Mean\left(\frac{\partial F(D)}{\partial D}\right)\Big|_{\substack{Region\ B \\ recovery}} \tag{7}$$

Where *F*(*D*) represents the force function versus displacement *D*. The region C corresponds to the stretching stage and stretching recovery

Table 5
Results of subjective evaluation of fabric wrinkling grades and curve parameters.

Sample No.	Subjective evaluation of fabric wrinkling grades							Parameters extracted from the mechanical test curve				
	Judge1	Judge2	Judge3	Judge4	Judge5	Judge6	Mean value	Dwr/mm	Hwr/cN	Fwr/cN	Scr/(cN/mm)	Str/(cN/mm)
1	2	2	1	2	2	1	1.67	0.58	20.1	13.8	651.4	703.5
2	2	3	3	3	3	2	2.67	0.20	9.4	6.2	707.8	601.8
3	4	3.5	3	3.5	3.5	3.5	3.50	0.07	7.2	9.1	663.7	818.0
4	3.5	4	4	3.5	3.5	3.5	3.67	0.05	2.6	5.3	775.1	679.3
5	3.5	3.5	3	3.5	3	3	3.25	0.39	8.2	7.3	712.4	682.3
6	2	1	2	2	2	2	1.83	0.72	29.9	18.8	591.4	501.0
7	3.5	4	3	3.5	3.5	3.5	3.50	0.18	11.3	7.6	724.3	492.8
8	4	4	4	4	4	4	4.00	0.10	4.4	5.3	743.3	729.7
9	3.5	3.5	3	3.5	3	3	3.25	0.18	4.9	5.0	834.3	710.2
10	3.5	3.5	3.5	3.5	3.5	3	3.42	0.07	3.8	4.7	804.3	730.4
11	3.5	3	4	3.5	3.5	3.5	3.50	0.19	10.1	8.6	775.1	762.0
12	3.5	3.5	3	3.5	3.5	3	3.33	0.17	15.7	10.1	676.5	764.4
13	3	2	3	2	3	2	2.50	0.61	17.6	13.3	702.5	692.9
14	3	3.5	3.5	3.5	3	3	3.25	0.36	12.6	8.8	715.9	706.4
15	4	3.5	4	4	3.5	4	3.83	0.18	1.3	2.1	801.0	728.5
16	3	3	3	3	3	3	3.00	0.84	14.9	10.7	700.1	555.9
17	5	5	5	5	5	5	5.00	0.12	0.7	0.9	705.9	765.2
18	4	4	4	4	5	5	4.33	0.13	2.4	2.6	815.4	725.3
19	2	1	2	2	2	2	1.83	0.61	27.2	16.3	647.8	562.5
20	3.5	3	3.5	3	3	3.5	3.25	0.23	5.3	4.6	777.3	635.1
21	1	1	1	2	1	1	1.17	1.58	17.2	13.9	713.8	702.9
22	3.5	3.5	3	3.5	3.5	3.5	3.42	0.06	10.7	8.4	372.1	662.7
23	3	3.5	3	3	3	3	3.08	0.23	10.5	8.9	593.7	758.6
24	3.5	4	3.5	3.5	3.5	3.5	3.58	0.09	3.9	6.4	804.4	691.4
25	4	4	5	4	5	4	4.33	0.11	1.3	1.1	766.7	768.2
26	4	3.5	4	3.5	3.5	3.5	3.67	0.16	7.5	5.5	723.2	715.5
27	3.5	3.5	4	4	3	3	3.50	0.32	2.3	4.2	802.1	739.5
28	3.5	3.5	3	3.5	3.5	3	3.33	0.27	4.8	6.5	793.8	708.8

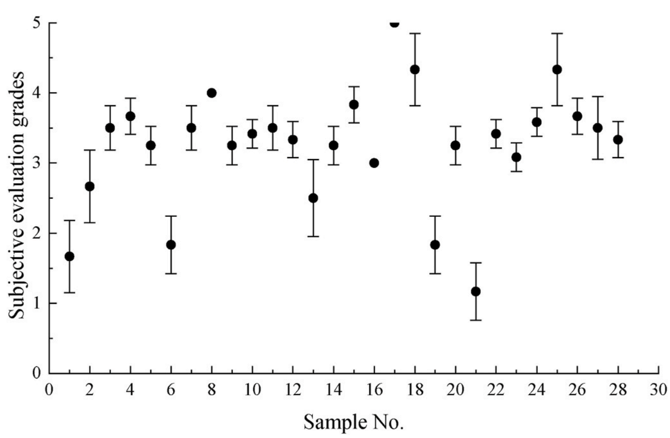


Fig. 8. Summary of subjective evaluation of fabric smoothness.

stage. In this region, the fabric begins to be unbent and stretched by the moving slab, and the curve increases sharply during the stretching stage. After that, the sample starts to recover along with a sharp decrease of the tension, and the moving slab returns to the starting position of the test.

Then, the stretch resilience slope S_{tr} fitted to the corresponding straight line section of the stretch recovery curve could be calculated by equation (8) to represent the elastic resilience of the fabric.

$$S_{tr} = Mean\left(\frac{\partial F(D)}{\partial D}\right)\Big|_{\substack{Region\ C\\ recovery}} \quad (8)$$

The five curve parameters were extracted from the measured force-displacement curve, and the statistical results are shown in Table 5.

5.2. Analysis of the subjective evaluation

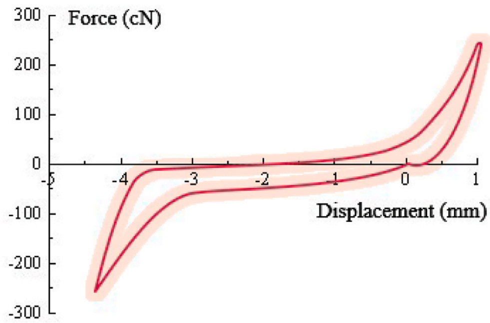
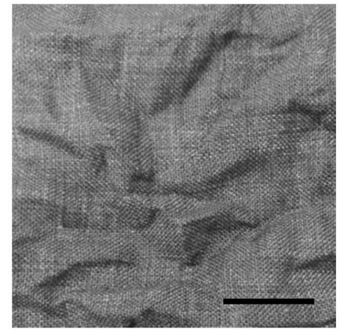
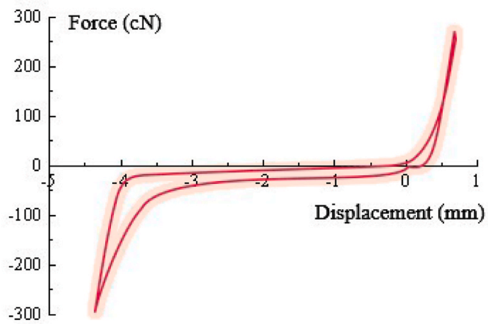
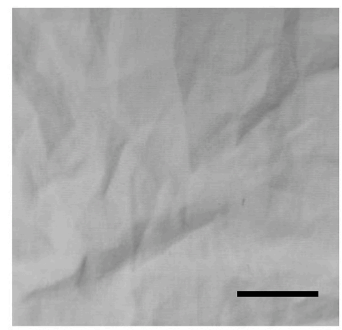
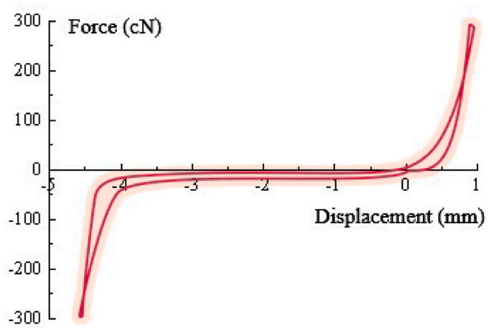
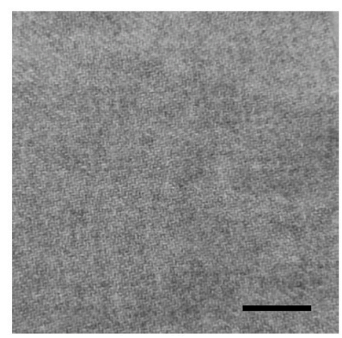
The average value of standardized subjective feeling performance is shown in Fig. 8. It can be intuitively seen that there is a small difference between the subjective evaluation results for each sample, but the grade error is not very large as indicated by the error bars fluctuating within one grade, which proves the consistency and effectiveness of the subjective evaluation. Samples 1#, 6#, 13#, 19# and 21# have relatively small subjective wrinkle grades ranging from 1 to 2.5, and the corresponding curve parameters *Dwr*, *Hwr* and *Fwr* are significantly larger than those of other samples. On the contrary, samples 8#, 17#,18# and 25# are ranked as relatively high wrinkle grades by subjective

Table 6
Correlation analysis of fabric wrinkle grades and curve curve parameters (T: Thickness, W: weight, WG: wrinkle grade).

	D_{wr}	H_{wr}	F_{wr}	S_{cr}	S_{tr}	T	W	WG
D_{wr}	1							
H_{wr}	0.773[b]	1						
F_{wr}	0.679[b]	0.953[b]	1					
S_{cr}	−0.457[a]	−0.714[b]	−0.765[b]	1				
S_{tr}	−0.601[b]	−0.478[a]	−0.373	0.232	1			
T	0.647[b]	0.765[b]	0.651[b]	−0.724[b]	−0.585[b]	1		
W	0.589[b]	0.752[b]	0.694[b]	−0.894[b]	0.462[a]	0.865[b]	1	
WG	−0.840[b]	−0. 842[b]	−0.770[b]	0.525[a]	0.549[b]	−0.691[b]	−0.582[b]	1

[a] Correlation is significant at the 0.05 level (double tail).
[b] Correlation is significant at the 0.01 level (double tail).

Table 7
The relationship between *WG*, the curve shape and the typical fabric image (scale bar: 1 cm).

Wrinkle grade	Typical curve shape	Typical fabric image
1~2.5		
2.5~3.5		
3.5~5		

evaluation, and their corresponding curve parameters are relatively small (see Table 5). This shows a good correlation between the wrinkle grades of fabrics and the curve parameters extracted by folding mechanical test.

In order to further analyse the relationship between fabric subjective wrinkle grades and curve parameters, the Spearman correlation analysis was carried out. The results are summarized in Table 6. The *Scr* shows good relationships with the fabric wrinkle grades at the level of 0.05, while other parameters D_{wr} (correlation coefficient = −0.840), H_{wr} (−0.842), F_{wr} (−0.770), S_{tr} (0.549) were significantly correlated with the fabric wrinkle grades at the level of 0.01, indicating that the curve parameters extracted from the folding test can reflect the main nature of fabrics in terms of wrinkling. Thus, the parameters can be used to predict the wrinkle grades of fabrics.

5.3. The construction of prediction model

To further investigate the relationships between subjective wrinkle grades and the curve parameters, a stepwise regression method was used under the 95% confidence interval to establish the prediction model by removing the insignificant parameters, which also lay down the way to predict the wrinkle grades of fabrics objectively by the proposed mechanical test. The criteria of $p<0.05$ and $p>0.10$ were respectively used to determine whether an independent variable was selected or removed from the regression equation. The samples numbered from 1# to 20# were used to develop the prediction model, as shown in equation (9):

$$WG_{pre} = -0.911D_{wr} - 0.118F_{wr} + 4.448 \quad (R^2 = 0.812) \tag{9}$$

Where, WG_{pre} is the predicted value of fabric wrinkle grades. Two parameters, deflection displacement *Dwr* and wrinkling residual force *Fwr*, are selected into the prediction model by stepwise regression algorithm, indicating that the fabric wrinkle grades is mainly determined by the bending performance of fabrics. The reasonably high coefficient of determination R^2 of the prediction model explains that the fabric wrinkle grades fits well with the extracted parameters. In addition, the F value = 38.970 by the analysis of variance (ANOVA), larger than the critical value $F_{0.05}(2,18) = 3.555$, further confirms that the regression model allows for predicting the subjective wrinkle grades using the selected mechanical parameters.

Table 7 shows the typical curve shape of wrinkle grades and the examples of the corresponding wrinkled fabric images, where the

Table 8
Comparison of subjective and objective evaluation of fabric wrinkling grades.

Sample No.	subjective evaluation	Objective evaluation	difference	Absolute value of error rate
A	3.42	3.41	0.01	0.2
B	3.08	3.18	−0.10	3.2
C	3.58	3.61	−0.03	0.8
D	4.33	4.22	0.11	2.5
E	3.67	3.65	0.02	0.5
F	3.5	3.65	−0.15	4.2
G	3.33	3.44	−0.11	3.3

wrinkle grade was integrated into three ranges, namely 1–2.5, 2.5–3.5 and 3.5–5, and the red curve represent the average value of different fabrics in the stated grade range. It can be seen that the fabric is very wrinkled in the case of wrinkle grade∈[1, 2.5], and the curve parameters, *Dwr*, *Hwr* and *Fwr* reach their maximum, while the slope *Scr* and *Str* are kept at minimum. The fabric is the smoothest and almost wrinkle-free in the case of wrinkle grade∈[3.5, 5], and its curve parameters are contrary to the case of wrinkle grade∈[1, 2.5]. The average values of the force-displacement curve for wrinkle grade∈[2.5, 3.5] is slimmer than the curve for wrinkle grade∈[1, 2.5] and broader than that for wrinkle grade∈[3.5, 5]. In other words, wrinkle grade is negatively correlated with the *Dwr*, *Hwr* and *Fwr*, while positively correlated with *Scr* and *Str*, which is highly consistent with the trend expressed by Table 6 and equation (9), confirming the feasibility and stability of the FWES.

5.4. The inspection of regression model

To further verify the validity of the constructed prediction model, the curve parameters extracted from test samples No. A-G were used for independent validation. The subjective evaluation of the fabric wrinkle grades was compared with the model prediction based on the measured curve parameters from the proposed mechanical test. The results are shown in Table 8. As can be seen, the difference of subjective evaluation and model prediction is less than 0.15, and the maximum absolute error rate is not larger than 4.2%. This indicates that the subjective and objective evaluation results have good consistency, and it also clarifies the curve parameters *Dwr* and *Fwr* from the folding process contain main information of fabric mechanics relating to its wrinkling. Therefore, the prediction model together with the proposed mechanical test provides an alternative method to characterize the fabric wrinkle grades.

6. Conclusions

A simultaneous mechanical test method and a prototype instrument, namely the FWES, were developed to characterize the surface wrinkling of fibrous sheet materials such as fabrics. A mechanical and geometrical insight into the connection between folding and wrinkling of textile materials was provided based on the power law. The results of experimental tests revealed that a folding test can grasp the main wrinkling features of fabrics, proving the great potential of using regular folding test to characterize the disordered wrinkling of textile materials. Five curve parameters, namely recovery slope of compression *Scr*, deflection displacement *Dwr*, wrinkle residual force *Fwr*, hysteresis distance *Hwr* and recovery slope of tension *Str*, were extracted from the force-displacement curve of the FWES. The results of statistical analysis and comparisons with subjective evaluation indicate that the extracted curve parameters contain the main information of appearance properties of fabrics, and can be used to characterize the wrinkling of fabrics. A prediction model was also constructed by stepwise regression analysis, which revealed that the wrinkle residual force (*Fwr*) and deflection displacement (*Dwr*) play important roles in wrinkle recovery properties of fabrics. The good prediction results of the model further verified the feasibility of using mechanical indices from folding progress to evaluate the wrinkling of fabrics. The proposed instrument, therefore, provides a convenient and effective way to quantify the wrinkling of fibrous sheet materials objectively.

CRediT authorship contribution statement

Caiqin Xiao: Investigation, Formal analysis, Methodology, Writing – original draft, preparation. **Fengxin Sun:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition. **Mohammad Irfan Iqbal:** Visualization, Methodology. **Li Liu:** Investigation, Formal analysis. **Weidong Gao:** Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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