From Theory to Practice: Improving the Foldcrack Resistance of Industrially Produced Triple Coated Paper

Arthas Yang [a] and Yepper Xie [a], Styron LLC, Shanghai, China 201203
Wang Renjung, Gold East Paper (Jiangsu), Zhenjiang, China 212132
[a]: Co-first author

Abstract: This study is based on earlier presented computer modeling and simulation of foldcrack resistance of multilayer coated paper [1-2]. This theoretical work suggested that foldcrack resistance can be improved by control of elastic modulus and thickness of the various layers and that the balance between stiffness and foldcracking is optimized by a layer structure consisting of a thin and stiff precoat layer covered by thick and strong middlecoat layer. The proposed mechanism is that the approach lowers stress development at coating surface during folding due to stress release within precoat due to crack formation and prevents crack propagation to the surface due to the strong middle layer.

In order to apply the novel theoretical concept in industrial production of coated paper, a quantitative method ("Fold Crack Area Ratio Test") was developed and validated. The test development is described in detail.
Extensive pilot coater trials were carried out to optimize foldcrack resistance of triple coated fine paper by the use of the theoretical concept. Latex elastic modulus and tensile strength as well as coatweight distribution were the main variables. The performance of the optimized system in industrial conditions was validated in subsequent mill trials.

Background

The manufacture of coated paper or board products such as magazines, books, boxes, cartons involves a folding operation. The objective of the folding step is to convert a sheet of paper, often printed, into the form that could be handled directly or indirectly, to undergo a further finishing process. Modern folding machines use two different methods for the finishing of printed products: knife folding and pocket folding, as shown in Fig. 1 [3]. Knife folders are popular for the folding of papers with higher basis weights. Pocket folders can handle sheets more rapidly as their speed is not bounded to the mechanical movement of a knife. Pocket folding is also quiet popular when several folds are required for the same sheet.

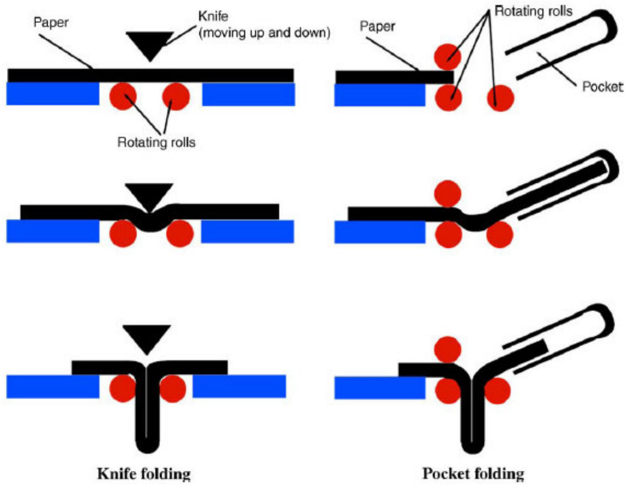


Fig.1: Schematic view of the folding process; both knife and pocket folding are shown; reprinted from ref. [3].

Paper folding comprises an extreme bending mechanism resulting in high-localized strains on coating layer as well as base paper. These large strains may introduce cracking within the coating layer, and sometimes, in base paper. The cracking, as a result, could leave an unsightly visible crack line along the fold when the coating fractures under the duress of the folding operation, which destroys the appearance (white line in printed area) or the functionality (for example, barrier) of paper/board products. In addition, the fracture line in the coating reduces the strength of the coated paper and increases the possibility of the magazine or coated article falling apart in the folds. These two problems are becoming even more critical with the reduction in fibre content through the use of more coating layers or fillers to save paper production cost.

Visual paper surface defects along folding line as a result of fold crack after printing are attracting more and more attention in China market. With the installation of new paper machines and state-of-art coaters, paper industry in China is developing very fast in terms of both production capacity expansion as well as technology evolution. Cost reduction while maintaining or improving product quality is the key market drive. One product trend in line with this market drive is to increase amount of coating color and to reduce the usage of wood fiber. Increasing coatweight could bring several technical benefits, eg., better coating coverage, higher sheet gloss, better ink hold-out, higher ink gloss, lower surface smoothness, etc.; however, two quality concerns are loss of stiffness and crack of paper during folding process. Fold crack problem for high basis weight paper is a major industrial concern right now.

Several attempts have been made in order to analyze the fold crack problem experimentally, and more importantly, to understand the mechanism and to validate technical solutions. Colley [18] developed a systematic method to compare the tensile strengths of papers after creasing and folding. Further work by Colley [19] suggested that cracks in the coating layers depend to a great extent on the base stock, and that the crack risk could be avoided by optimizing the degree of beating. Guyot [20] suggested that fold-crack resistance is related to coating penetration into the base paper and therefore, the ability of the base paper to resist buckling at the inside of the fold. Jopson and Towers [21] continued the work by performing a systematic study of how the relationship between the properties of the coating layer and of the base stock affects cracking. Cracking failure within the base stock was caused by a weak base stock in combination with a stiff coating layer. Barbier [22] showed that the fold cracking can be eliminated by reducing the thickness of the paper. Further studies on mechanical properties of coating layers and its impact on fold crack resistance are also reported [23-25]. Higher binder content and larger particles are both favorable for coating strength. Clay generally gives a higher in-plane stiffness and strength than GCC, due to its orientation. On the other hand, clay gives a lower out-of-plane strength for the same reason. Numerical simulations by Rättö [26] suggested that the bending and shearing of pigmented coatings are far more complex than the situation described by one dimensional beam bending.

In the meantime, the combination of experimental observations and numerical analysis brought new insights into the fold crack problem. Carlsson *et al* [27] used the finite element method to model the creasing of paper. Starting from the point that the control of paper folding is displacement controlled rather than force controlled and subsequently used deformation angles of 1^{o}, they reported that at constant folding angles, stresses at the fold are higher in CD than in MD. Barbier *et al* [28] employed significantly greater levels of straining and included a plastic failure criterion, and reported that cracking did not take place in thinner papers due to the small strains in the top coating layer. Salminen *et al* [2, 29] carried out simulations based on different coating formulations in order to optimize the parameters to balance coating stiffness and fold crack resistance. It was suggested that the best balance between cracking resistance and raw material cost was achieved with a triple-coated paper. They also suggested that, since the strains are largest in the outer coating layer, this layer should be made flexible while bending stiffness and rigidity could be achieved with a stiff coating layer in the middle or at the bottom. The numerical simulations were confirmed by experimental results, where it was suggested that foldcrack resistance can be improved by control of elastic modulus and thickness of the various layers and that the balance between stiffness and foldcracking is optimized by a layer structure consisting of a thin and stiff precoat layer covered by thick and strong middlecoat layer. The proposed mechanism is that the approach lowers stress development at coating surface during folding due to stress release within precoat due to crack formation and prevents crack propagation to the surface due to the strong middle layer.

This study is based on earlier presented computer modeling and simulation of foldcrack resistance of multilayer coated paper [1-2]. Theoretical work suggested that foldcrack resistance can be improved by control of elastic modulus and thickness of the various layers and that the balance between stiffness and foldcracking is optimized by a layer structure consisting of a thin and stiff precoat layer covered by thick and strong middlecoat layer. A quantitative method ("Fold Crack Area Ratio Test") was developed and validated. Extensive pilot coater trials were carried out to optimize foldcrack resistance of triple coated fine paper by the use of the theoretical concept.

Latex elastic modulus and tensile strength as well as coatweight distribution were the main variables. The performance of the optimized system in industrial conditions was validated in subsequent mill trials in a Chinese paper mill.

Materials and Methods

There are two kinds of problems caused by paper folding: (1) loss of mechanical strength after folding paper for several times; (2) a visual white line defect after folding paper (usually printed). For problem (1), as described in previous publications [1-2], the Residual Strength test method was developed to measure the percentage of tensile break-up strength of paper after and before folding, to evaluate how the paper could maintain mechanical strength after being folded. For problem (2), in industrial practice, visual rating test method was adopted to incorporate a panel of people to give rating on the fold crack resistance of coated paper (1 = worst, 10 = best). This visual test is qualitative and tester dependent, and therefore not reliable.

To quantitatively characterize the fold crack performance, a new method – Fold Crack Area Ratio (FCAR) test was developed. Detail of this test was as follows:

- Step 1, sample preparation: conditioned paper samples under constant temperature and moisture were cut along MD direction into strips with dimension of 9 ¼ by 1 ¾ inches.
- Step 2, sample printing: paper samples were printed with black ink on Prufbau or IGT printability tester, under constant temperature and moisture.
- Step 3, folding line creation: after ink drying, paper samples were folded using IGT / Prufbau printability tester under constant load to create a folding line.
- Step 4, magnified pictures of folding line: the folded paper samples were then placed under microscope to take magnified pictures of the folding line, under constant magnification of 9.1. The angle of folding line was set constant at 45 degrees. Eight pictures were taken for one paper sample.
- Step 5, image analysis: magnified pictures were analyzed using image analysis software with gray scale identification capability (to compare the grey scale of pixels in picture and identify regions inside the manually set grey value threshold); white regions in the picture along folding line, caused by coating or base paper failure, were identified. The average area of white regions and its standard deviation were calculated.
- Step 6, FCAR result: the Fold Crack Area Ratio was calculated using the following equation:

$$\text{Fold Crack Area Ratio} = \frac{\text{Total Area of White Regions}}{\text{Total Area of the Picture}} \cdots\cdots \text{Eq. (1)}$$

Fold Crack Area Ratio result is a dimensionless number, with unit of “1”. Given the constant magnification used during measurement, total area of the picture was the same. Therefore, Fold Crack Area Ratio result could represent the fold crack performance: the higher the FCAR the result is, the worse the paper samples perform in terms of fold crack. A pictorial explanation could be found in Fig. 2.

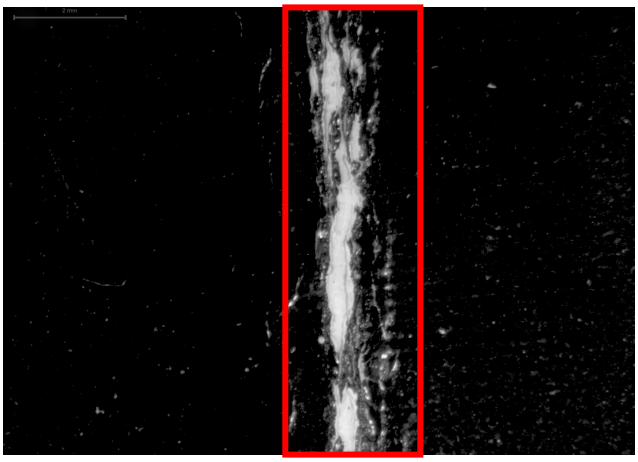


Fig.2: Schematic picture of Fold Crack Area Ratio test; white regions in red rectangle represent the crack area along the folding line; white spots outside the red rectangle is not counted into the calculation of fold crack area.

Lab, pilot coater and mill trial experiments were designed, in sequence, to test and validate the following hypothesis:

- 1st hypothesis: the Fold Crack Area Ratio test is a reliable test to evaluate foldcrack performance of coated paper samples;
- 2nd hypothesis as developed and partly validated in reference [1-2]: foldcrack resistance can be improved by control of elastic modulus and thickness of the various layers, and the balance between stiffness and foldcracking could be further optimized by a layer structure consisting of a thin and stiff precoat layer covered by thick and strong middlecoat layer.

Modulus of coating layer and coating thickness are the main changing parameters in the experiment design. Modulus of coating layer was adjusted by: (1) picking carboxylated Styrene-butadiene Latex with optimization on elasticity. Latex elastic modulus is closely related to the glass transition temperature. Latex with lower Tg would provide lower elastic modulus (and higher flexibility) to coating layer and help improve fold crack resistance. However, it is also well understood that elastic modulus of latex film (and therefore elastic modulus of coating layer) could vary on temperature and frequency of deformations, and Latex Tg should not be chosen as the only parameter to represent elastic modulus [3]; (2) the dosage of starch. It is generally believed that starch film is very stiff, and increasing starch dosage would increase coating modulus, and make fold crack resistance worse; and (3) the dosage of Latex. Increasing Latex dosage is believed to reduce coating modulus and increase coating flexibility, therefore allowing improvement of foldcrack resistance. Thickness of coating layers was controlled by coatweight. Strength of coating layer was adjusted by adjusting Latex dosage and choosing high-strength Latex technology. For details of the raw materials, please refer to Table 1.

Table 1: Detailed coating formulations, and coatweight of model coated paper systems

Raw Materials	**Name**	**Supplier**	**Key Properties**	**Note**
Latex	SPA 001	Styron LLC	Tg* = -6.5 °C Particle Size = 150nm	Carboxylated Styrene-Butadiene Latex, for pre coating layer without direct interaction with ink during printing process, with tailor-made optimization on elasticity
Latex	SPA 002	Styron LLC	Tg = +5°C Particle Size = 150nm	Carboxylated Styrene-Butadiene Latex, for pre coating layer without direct interaction with ink during printing process

Latex	SPA 003	Styron LLC	Tg = +16 °C Particle Size = 140nm	Carboxylated Styrene-Butadiene Latex, for top coating layer with direct interaction with ink during printing process
Latex	SPA 004	Styron LLC	Tg = +16 °C Particle Size = 90nm	High strength Carboxylated Styrene-Butadiene Latex offering 20% strength improvement vs. SPA 003, for coating layer with direct interaction with ink during printing process, with tailor-made optimization on elasticity
Starch				Hydroxyethylated corn starch

* Tg represents glass transition temperature.

The 1st lab experiment was designed to test the 1st hypothesis: the relevance of Fold Crack Area Ratio test results to real fold crack performance. The concept is to design various model coated paper samples with designed performance difference in terms of foldcrack. The foldcrack difference was controlled by Latex dosage and coatweight: it is believed that increasing Latex dosage would help improve foldcrack, while increasing coatweight would make foldcrack worse. The Latex was not changed in this study to reduce the variables. Detailed formulations were listed in Table 2.

Coating colors were prepared using a standard method by adding pigment slurry (ground calcium carbonate from OMYA), carboxylated styrene-butadiene Latex, CMC (FinnFix FF10), caustic and distilled water in sequence to achieve the target the coating solid and pH value. The experiments were performed in Styron Shanghai Paper Lab. The coating colors were then applied onto a woodfree paper with basis weight of 143gsm, with a laboratory web-coater. The coatweight is carefully controlled to reduce variation in both MD and CD directions.

Table 2: Detailed coating formulations, and coatweight of model coated paper systems

Experiment Points	**1st Coating Layer**	**Coating Formulation**	**2nd Coating Layer**	**Coating Formulation**	**3rd Coating Layer**	**Coating Formulation**	**Base Paper**
No. 1	20gsm	100p C65 15p SPA 001*	15gsm	100p C65 15p SPA 001	N/A	N/A	143gsm Woodfree
No. 2	20gsm	100p C65 10p SPA 001	N/A	N/A	N/A	N/A	143gsm Woodfree
No. 3	20gsm	100p C65 10p SPA 001	15gsm	100p C65 10p SPA 001	15gsm	100p C65 10p SPA 001	143gsm Woodfree
No. 4	20gsm	100p C65 20p SPA 001	15gsm	100p C65 20p SPA 001	15gsm	100p C65 20p SPA 001	143gsm Woodfree

*All formulations contain same amount of CMC, pH =8.5 and coating color solid content kept at 70%.

Pilot coater trials were later performed to test the 2nd hypothesis in pilot production level: foldcrack resistance can be improved by control of elastic modulus and thickness of the various layers, and the balance between stiffness and foldcracking could be further optimized by a layer structure consisting of a thin and stiff precoat layer covered by thick and strong middlecoat layer. The detailed experimental design was as follows:

- Point I: the reference reel.
- Point II: SPA 001 with optimized elasticity was used for 1st and 2nd coating layers to reduce coating elastic modulus. In 3rd coating layer, Latex SAP004 with higher strength and optimized elasticity was used. These adjustments would reduce elastic modulus of all 3 coating layers, and principally the 3rd coating layer of Point II has higher strength than Point I.
- Point III: a thick flexible strong layer was created for 2nd coating layer by increasing Latex dosage and coatweight while decreasing starch dosage. Coatweight for 1st coating layer, which contains higher amount of starch, was slightly reduced, to model the thin stiff inner layer. The overall coatweight was increased by 10gsm.

Coating colors were prepared using a standard method by adding pigment slurry (ground calcium carbonate from OMYA), carboxylated styrene-butadiene Latex, cooked starch, lubricant (calcium sterate type), caustic and distilled water in sequence to achieve the target the coating solid and pH value, in Styron Center of Excellence of Paper Coating located in Samstagern, Switzerland. In certain formulations, thickener (FinnFix FF10 CMC slurry) was added to adjust the Brookfield viscosity at the same level to promote good machine runnability. The coating colors were then applied onto a woodfree paper with basis weight of 105gsm.

The pilot coater running parameters are: for 1st coating layer with pre-metered coating station, machine speed is 1500m/min; for 2nd coating layer with bent blade coating station, machine speed is 1600m/min; for 3rd coating layer with stiff blade coating station, machine speed is 1600m/min. Coating layers were applied one after each other. For 3rd coating layer, top side was first coated, followed by bottom side. The rod load or blade load was carefully controlled to achieve target coatweight and to minimize coatweight variation in both MD and CD directions. The coated paper was then calendered with super-calender to achieve target paper gloss of 70 degrees. The parameters studied in the pilot coater trial include carboxylated styrene-butadiene latex, coatweight, coatweight distribution, and latex dosage in different layers. Detailed coating formulations are listed in Table 3.

Table 3: Detailed coating formulations, and coatweight of pilot coater trial coated paper samples

Experiment Points	**1st Coating Layer**	**Coating Formulation**	**2nd Coating Layer**	**Coating Formulation**	**3rd Coating Layer**	**Coating Formulation**	**Base Paper**
Point I	16gsm	100p C65 10.5p SPA 002 8.0p Starch Solid =62.0%	22gsm	100p C65 7.5p SPA 002 6.0p Starch Solid =68.0%	22gsm	100p C95 11p Latex SPA 003 Solid =69.0%	105gsm Woodfree
Point II	16gsm	100p C65 10.5p SPA 001 8.0p Starch Solid =62.0%	22gsm	100p C65 7.5p SPA 001 6p Starch Solid =68.0%	22gsm	100p C95 11p Latex SPA 004 Solid =69.0%	105gsm Woodfree
Point III	14gsm	100p C65 10.5p SPA 001	34gsm	100p C65 9p SPA 001	22gsm	100p C95 11p SPA 004	105gsm Woodfree

	8.0p Starch	3.0p Starch	Solid =69.0%
	Solid =62.0%	Solid =68.0%	

* All formulations in same layer contains same amount of Lubricant, Defoamer and Insolubilizer, pH =8.5.

Mill trials were performed in one Chinese paper mill to further test the 2nd hypothesis in mill production level. The detailed experimental design was as follows:

- Trial I: the reference reel.
- Trial III: SPA 001 with optimized elasticity was used for 1st and 2nd coating layers to reduce coating elastic modulus. In 3rd coating layer, Latex SAP004 with higher strength and optimized elasticity was used.
- Trial II: coatweight of 2nd coating layer was increased to create a strong thick middle layer, while coatweight of 1st coating layer which contains higher amount of starch was reduced to create a thin stiff layer. Coatweight of 3rd coating layer was reduced to maintain the same total coatweight.

The mill trials were run on a woodfree paper with base weight of 90gsm, and the machine running parameters are: for 1st coating layer with pre-metered coating station, machine speed is 1350m/min; for 2nd coating layer with bent blade coating station, machine speed is 1650m/min; for 3rd coating layer with stiff blade coating station, machine speed is 1650m/min. For 3rd coating layer, top side was first coated, followed by bottom side. Coated paper was then calendered to achieve target paper gloss of 70 degrees. Paper samples were collected and fold crack test was performed afterwards. Detailed coating formulations and coated paper compositions are listed in Table 4.

Table 4: Detailed coating formulations, and coatweight of mill trial paper samples

Experiment Points	**1st Coating Layer**	**Coating Formulation**	**2nd Coating Layer**	**Coating Formulation**	**3rd Coating Layer**	**Coating Formulation**	**Base Paper**
Trial I	16gsm	100p C65	22gsm	100p C65	22gsm	100p C95	90gsm
		10.5p SPA 001		7.5p SPA 001		11p SPA 003	Woodfree
		8.0p Starch		5p Starch		Solid =69.0%	
		Solid =62.0%*		Solid =68.0%			
Trial II	13gsm	100p C65	30gsm	100p C65	17gsm	100p C95	90gsm
		10.5p SPA 002		7.5p SPA 002		11p SPA 004	Woodfree
		8.0p Starch		5.0p Starch		Solid =69.0%	
		Solid =62.0%		Solid =68.0%			
Trial III	16gsm	100p C65	22gsm	100p C65	22gsm	100p C95	90gsm
		10.5p SPA 002		7.5p SPA 002		11p SPA 004	Woodfree
		8.0p Starch		5.0p Starch		Solid =69.0%	
		Solid =62.0%		Solid =68.0%			

* All formulations in same layer contain same amount of Lubricant, Defoamer and Insolubilizer, pH =8.5.

Results and Discussions

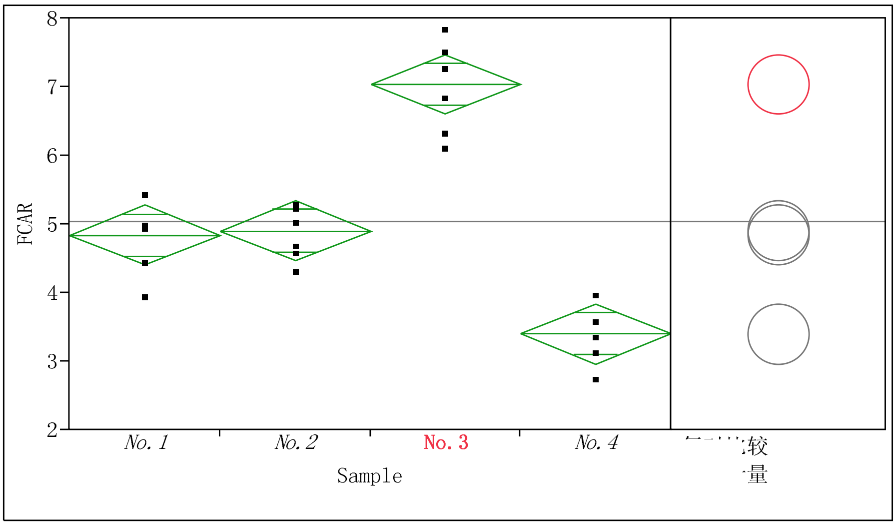
The relevance of Fold Crack Area Ratio test results to real Fold Crack performance was evaluated in the lab experiment. It is expected that samples with higher coatweight and less latex in coating formulations, given that the other parameters maintain the same, would have worse fold crack resistance. Detailed test results were listed in Table 5. Statistical analysis was performed to test whether the fold crack performance of different model paper samples showed significant difference. The statistical analysis results are plotted in Fig .3.

It could be seen that samples No.4 and No.3 showed significant difference in terms of “Fold Crack Area Ratio”, which is in line with the expectation that adding more latex (10p in sample No.3 and 20p in sample No.4) would help improve fold crack resistance. Samples No.1 and No.2 showed similar fold crack resistance performance. The results justify the relevance of “Fold Crack Area Ratio” test on evaluating the real fold crack resistance performance. It is as well interesting to see how the combination of latex dosage and coatweight influences the fold crack resistance performance: sample No.2 with 20gsm coatweight and 10p latex, shows similar performance with sample No.1 with 35gsm coatweight and 15p latex, which are both worse than sample No.4 with 50gsm coatweight and 20p latex. This gives an indication on how to balance the Latex dosage and coatweight to get desired fold crack resistance performance.

Table 5: “Fold Crack Area Ratio” test results of model coated paper samples.

Sample	**Test Run No. 1**	**Test Run No.2**	**Test Run No.3**	**Test Run No.4**	**Test Run No.5**	**Test Run No.6**	**StDev, %**
No. 1	4.01	4.48	5.04	5.04	5.49	4.99	11
No. 2	4.36	5.08	4.74	5.34	5.28	4.63	8
No. 3	6.39	6.15	6.89	7.58	7.9	7.33	9
No. 4	2.8	3.39	3.64	3.19	4.02	3.4	12

Fig. 3: Statistical analysis on “Fold Crack Area Ratio” test results of model coated paper samples



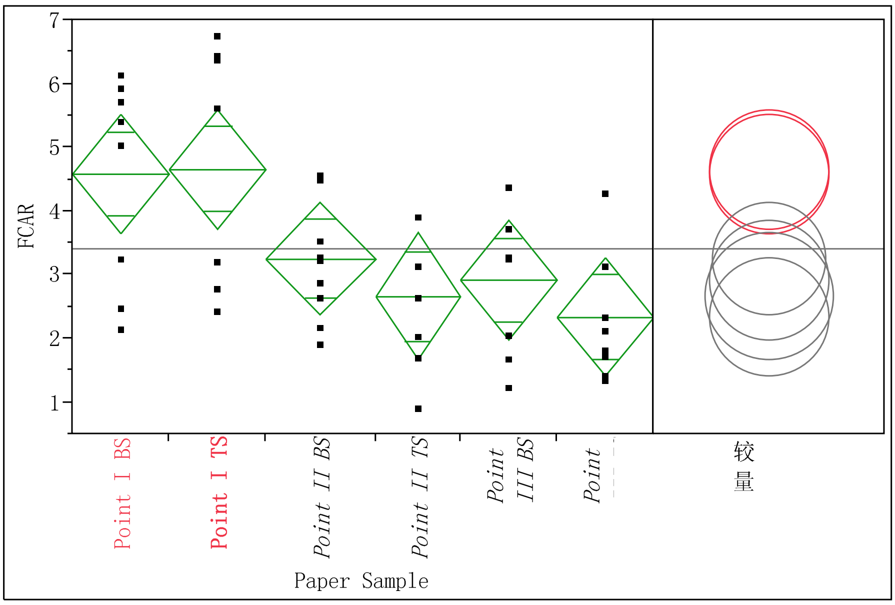
Fold Crack Area Ratio test results of pilot coater trial samples were summarized in Table 6. The average and standard deviation for each experiment point were calculated and listed. Statistical analysis was then performed to compare results among Sample I, Sample II and Sample III to detect whether there is statistically significant difference. The results are plotted in Fig. 4 and listed in Table 6 as well.

It could be seen that sample II and samples III showed statistically significant difference with sample I; while, the difference between sample II and sample III is not significant. This is true for both top and bottom sides. The explanation would be by simultaneously changing latex from one with high elastic modulus (high Tg) to one with lower elastic modulus (low Tg) for pre coating, and choosing a top coat latex with higher cohesive strength (low Tg), the fold crack resistance could be improved. This is in line with what has been reported in previous research [1, 2]. From sample II to sample III, the coatweight was increased by 10gsm (from 60gsm to 70gsm); it is expected that the fold crack resistance of sample III would become worse. However, the test results did not support such hypothesis. The explanation would be changing the coatweight distribution and coating color formulations to create a thin sacrifice layer, to lower stress development at coating surface during folding and prevent crack propagation to the surface due to the strong top layer, would help improve fold crack resistance. This is in line with what has been reported in reference [1, 2].

Table 6: Fold Crack Area Ratio test result of pilot coated trial samples.

Experiment Samples	Point I - TS	Point I - BS	Point II - TS	Point II - BS	Point III - TS	Point III - BS
Result 1	5.04	4.61	1.77	3.61	3.16	1.30
Result 2	5.04	5.09	2.77	2.79	2.01	3.19
Result 3	4.61	4.29	2.72	2.72	1.42	2.72
Result 4	4.72	4.22	2.15	3.75	2.66	2.75
Result 5	4.66	5.03	2.78	3.29	2.20	4.45
Result 6	4.46	4.31	2.61	4.03	1.89	3.33
Result 7	3.91	4.58	2.68	3.93	2.99	2.32
Result 8	4.85	4.50	3.41	2.95	2.41	3.31
Average	4.66	4.58	2.61	3.38	2.34	2.92
Stdev, %	7.3	6.7	17.3	14.4	23.3	29.1

Fig. 4: Statistical analysis on “Fold Crack Area Ratio” test results of pilot coater trial paper samples.



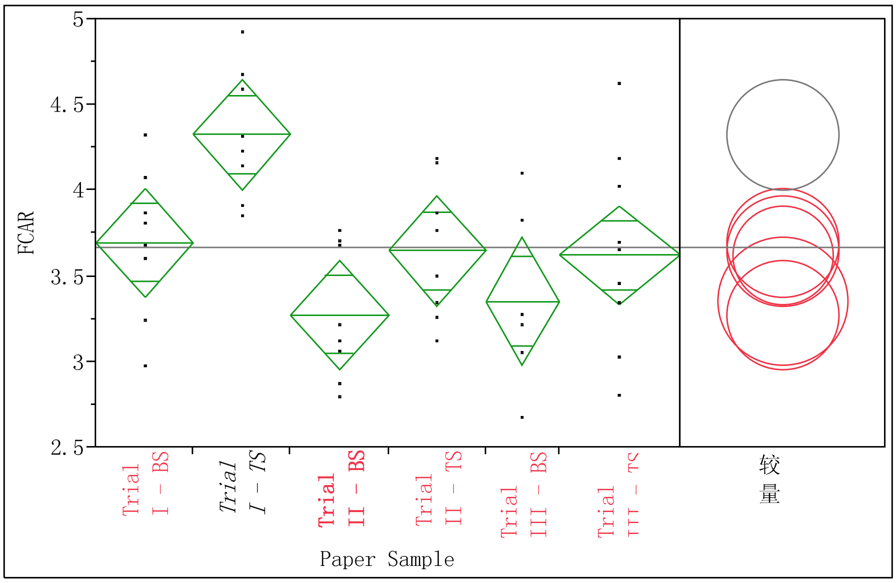
Fold crack test results of mill trial samples were summarized in Table 7. The average and standard deviation for each experiment point were calculated and listed. Similar to the pilot coater trial results, a statistical analysis was then performed to compare results among Trial I, Trial II and Trial III to detect whether there is a statistically significant difference among the samples. The results are plotted in Fig. 4 and listed in Table 7 as well.

It could be seen from the test results that for topside, Trial – I shows significantly worse fold crack resistance than Trial – II and Trial – III. The explanation would be the same with pilot coater trial results: by simultaneously changing latex from one with high elastic modulus to one with lower elastic modulus for pre coating, and choosing a top coat latex with higher cohesive strength, the fold crack resistance could be improved. While, it is worth noting that Trial II and Trial III did not show significant difference for both top and bottom side. Although we intentionally create a thin bottom layer in the 1st coating, and a thick middle layer to protect the crack if it forms during folding, during the mill trial the adjustment on Latex and starch dosage might be too small to provide enough improvement on fold crack resistance that could be detected by the test. This indicates that adjustments on coating formulations and coating layer thickness need to be beyond certain threshold for improvement in fold crack resistance to be clearly seen from end-user's perspective.

Table 7: Fold Crack Area Ratio Test Result of pilot coated trial samples.

Experiment Points	**Trial I - TS**	**Trial I - BS**	**Trial II - TS**	**Trial II - BS**	**Trial III - TS**	**Trial III - BS**
Result 1	4.92	3.87	3.87	3.06	3.45	3.65
Result 2	4.67	2.97	4.16	2.87	3.02	2.8
Result 3	4.31	3.24	3.12	3.68	3.45	3.21
Result 4	3.85	3.60	3.76	3.12	4.18	3.82
Result 5	4.23	4.32	3.26	2.79	3.69	3.05
Result 6	4.14	3.68	3.34	3.21	3.34	3.27
Result 7	3.91	4.07	4.18	3.7	4.02	2.67
Result 8	4.59	3.97	3.50	3.76	4.62	4.10
Average	4.33	3.71	3.65	3.27	3.72	3.32
Stdev, %	8.1	11.2	10.4	11.1	13.1	14.1

Fig. 5: Statistical analysis to compare the fold crack area ratio test result of fold crack area ratio test results.



Another interesting point that we observed during mill trials is, for two coated paper samples with similar coating design and same coat weight, a 150gsm sample shows more severe fold crack than a 157gsm sample. The only difference between these two samples is that the 150gsm sample contains 7% higher BCTMP content. This indicated that base paper plays a key role in determining fold crack resistance as well, and simultaneous optimization of base paper and coating layer is necessary to get the expected performance.

Conclusions

In this paper, we implemented the theoretical approach published in previous research [1-2] in industrial practice to improve the fold crack resistance of triple coated paper, to address the quality concern on fold crack for high grammage coated paper with high coatweight. It is demonstrated that lowering the elastic modulus of carboxylated styrene-butadiene latex to lower the compressional stress and increasing the elongational strength of coating layer (especially top coating layer) by choosing stronger latex products, the fold crack resistance could be improved. It is further demonstrated that creating a thin, stiff, sacrifice layer to release the folding energy due to crack formation which would be further prevented by a thick strong outer layer, would allow the coatweight to be further increased while maintaining similar fold crack resistance performance. This is demonstrated in both pilot coater trials and subsequent mill trials. This approach is especially fit for applications where bending stiffness and fold crack resistance need to be balanced.

However, it should be noted that other approaches is applicable as well to improve fold crack resistance, for example, lowering the compression stress by taking out brittle components from the coating color (eg. starch), increasing elongation strength of coating layer by simply increasing latex addition level, and reducing paper thickness to reduce the elongation strain accumulated in the coating surface. Usually these approaches work very well when improvement in fold crack resistance is more critical while bending stiffness could be sacrificed to certain extent. In the meantime, fold crack resistance improvement is a systematic optimization project, involving not only optimization of coating layer, but also base paper composition, moisture profile in coated paper, folding process design, etc. The approach implemented and validated in this article could possibly be used to paper/board products immediately as a short-term remedy; but, the systematic approach is preferred to consider more influencing parameters, and optimize the system simultaneously.

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