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Mechanisms of perception of laid lines in Japanese paper

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Abstract Laid lines are observed frequently in Japanese paper. For restoration of historic document paper, the laid line intervals should be consistent between the restoration paper and the original paper for harmonized appearance. Considering this prerequisite, the perception mechanisms of the laid lines are discussed. Laid lines can be easily observed against backlight. However, there are several cases where laid lines are not visible against backlight, but are clearly visible with diffuse reflected light. With paper sheets formed on screens with short bamboo splint pitches, laid lines were observed only with diffuse reflected light. Within these sheets, there was no fiber mass distribution or surface roughness that correlated with the periodicity of the laid lines. On the other hand, paper sheets produced using long splint pitches exhibited light transmission unevenness, fiber mass unevenness, and surface roughness. Microscopic observations using two-way low-angle illumination revealed the following mechanism. In the flow sheet-forming method, fibers are oriented strongly in the cross-splint direction in the first layer while some fibers rotate and become aligned along the interspaces between the splints in the second layer during dehydration. Bidirectionally oriented fibers perpendicular to each other result in a contrasting reflectivity perceived as laid lines.

Key words Bamboo splints · Fiber orientation · Japanese paper · Laid lines · Screen

Introduction

In the manufacture of Japanese paper, the device that corresponds to a wire for dehydrating a fiber suspension to form a web in modern papermaking is called a screen, or *su*, in Japanese. It consists of bamboo or thatch splints of equal thickness that are aligned parallel, evenly spaced, and bound with threads. The traces of the splints, generally called laid lines, or *sunome*, sometimes appear clearly in the sheet. Figure 1 shows photographs of a screen, a close-up of the screen, and an example laid line of actual historic document paper photographed against backlight as a transmitted light image. The laid lines appear as stripes with regular spacing intervals. The pitch of the regularity is the same as that of the screen, or it might be slightly shorter if the sheet shrinks during drying.

The restoration and repair of paper properties such as historic documents and paintings has become a significant concern with respect to the inheritance of historic, cultural, and artistic values. In fact, its importance and the related operations have become widespread in the world. Japanese paper is frequently used for repairing paper properties and, for the selection of an adequate sheet, the laid line interval should be consistent with that of the original paper under restoration in order to achieve good harmony with regard to their visual appearance.[1] For this purpose, methods to count laid lines have been developed.[2] In addition, it is necessary to consider the sharpness and density contrast. Therefore, the factors affecting the appearance of laid lines to the human eye need to be clarified.

The laid lines in a sheet of paper can be easily perceived by the human eye against backlight. For greater precision, transmitted light distribution over a sheet of paper obtained using the film transmission mode of a flatbed image scanner is recommended. Figure 2 shows the transmitted light images of a sheet of paper handmade from *kozo* (paper

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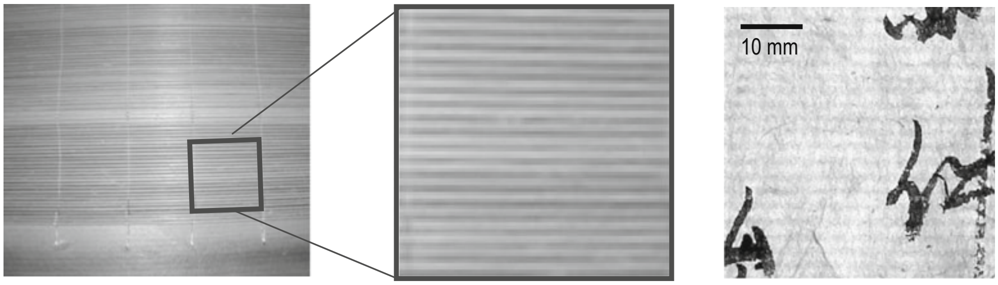


Fig. 1. Screen (*su*) and laid lines observed in sheet of historic paper against backlight

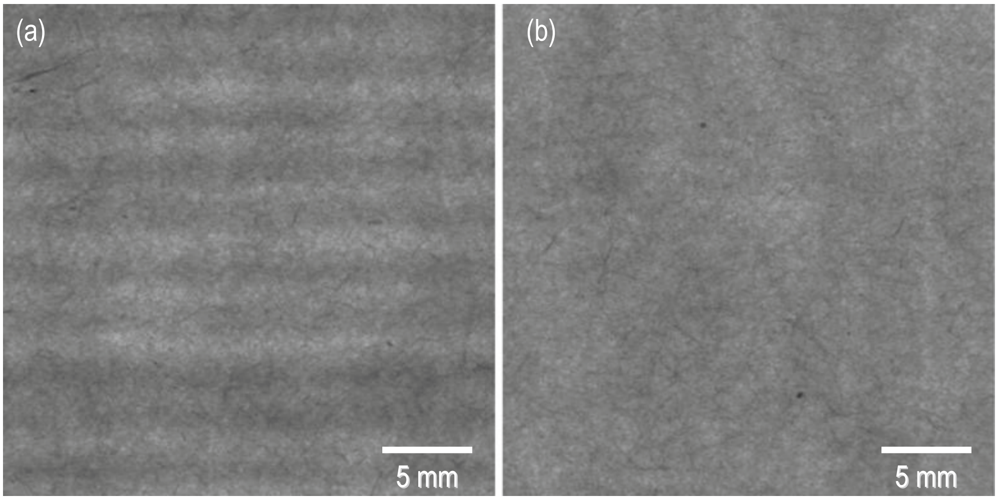


Fig. 2. Transmitted light scanner images of paper sheets with laid lines resulting from **a** 3.03-mm and **b** 1.21-mm splint pitches

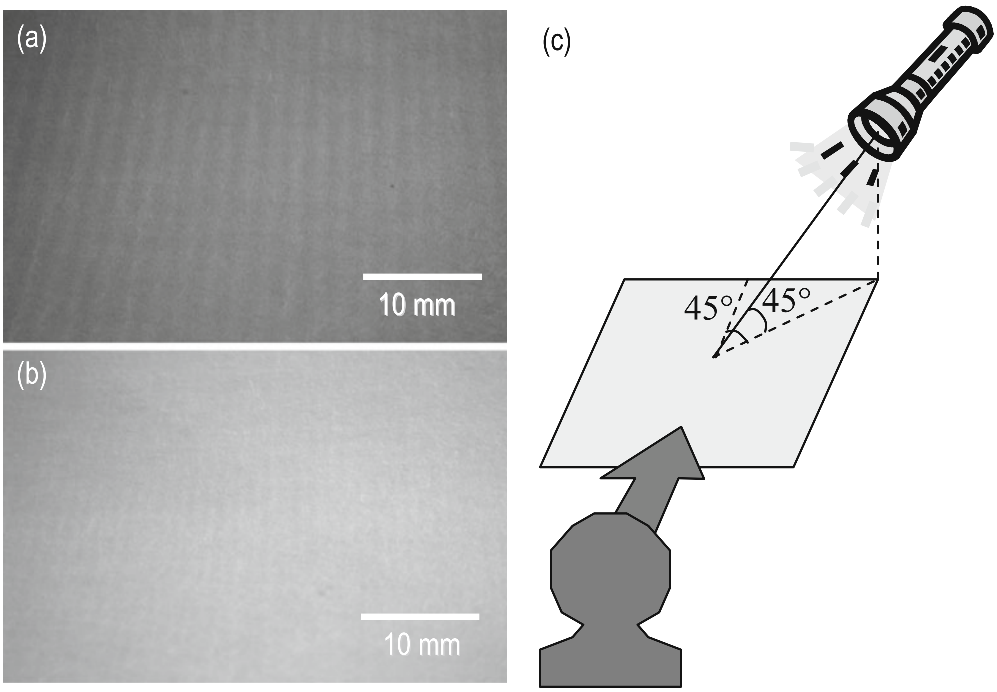
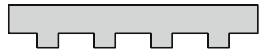
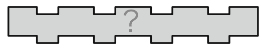
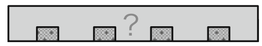


Fig. 3. Appearance of laid lines due to **a** 3.03-mm and **b** 1.21-mm splint pitches with **c** diffuse reflected light

mulberry, *Broussonetia papyrifera*) fibers by using screens with a pitch of 3.03 and 1.21 mm. The frequencies of these pitches are 10 and 25 lines, respectively, per *sun* (= 30.3 mm), based on the Japanese domestic unit system. Laid lines formed due to splints and having a pitch of 3.03 mm are clearly visible. However, laid lines with a pitch of 1.21 mm are unclear, not only in this image but also when general backlighting is used. This is not because the pitch is too short to be perceived by the human eye. Even though this image is magnified to observe the details, lines at regular intervals cannot be found; however, the uneven sheet formation can be clearly observed. Nevertheless, this fact does not imply that laid lines with a short pitch cannot be recognized. Figure 3 shows diffuse reflected-light images of sheets under

Table 1. Predicted laid line formation and appearance

(A) Dense lines in transmitted light images (clearer for larger interspaces of splints)	
(a) Fibers clogging between splints	
(b) High- and low-density distribution	
(B) Observation possible only in reflected light images on the screen side	
(a) Fibers clogging between splints	
(b) Concentration of additives between splints	

the condition of the light path of illumination depicted in Fig. 3c. The samples are sheets formed on screens with 3.03-mm and 1.21-mm splint pitches, respectively, from *gampi* (*Diplomorpha sikokiana*) fibers. The laid lines aligned in parallel can be observed clearly even for a sheet formed on a screen with a pitch as low as 1.21 mm, which was invisible in the transmitted light image. How clearly the laid lines are visible depends on the direction of illumination, but this configuration provided the best illumination condition for clear observation.

Considering different observation techniques, the manner in which the laid lines appear can be classified into several types. Table 1 shows several predicted possible patterns along with the schematic cross-sectional views. Pattern A denotes the case in which the laid lines are visible in transmitted light images. Two subcases are possible: (a) ridges are formed by fiber plugging into the interspaces present between the splints of a screen and (b) the density distribution is uneven due to flattening of the ridges during the drying or pounding processes. Pattern B denotes the case in which the laid lines are visible in reflected light images. The two possible subcases of this pattern are: (a) the backside of the ridges mentioned in case (a) of pattern A are grooves, and as a result the thickness is homogeneous and case (b) additives are concentrated inside the ridges and their color and light reflectance are different from those of the surroundings. However, these subcases contradict the facts: in case (a), laid lines would be visible from both sides, while in case (b), they would be visible in the transmitted light image as well. Moreover, *neri*—a viscous aqueous solution of polysaccharides extracted from *Hibiscus manihot* (*Abelmoschus manihot*)—was the sole additive to the paper samples analyzed in this work. *Neri* becomes transparent film-like pieces in the sheets and thus case (b) of pattern B does not apply to these samples. Therefore, there appears to be another mechanism for the laid lines visible using diffuse reflected light.

An uneven distribution of fibers is likely to occur if dehydration does not proceed at the same rate across the entire sheet. To prevent this, the screen must have evenly interspaced splints in addition to lightness, rigidity to hold a heavy fiber suspension, and low absorption. Taking into consideration the abovementioned factors, we can surmise that evenly spaced bamboo splints constitute a most satisfactory structure.

Advanced wood and fiber processing techniques allow the manufacture of thin splints and connecting threads. The dehydration rate and the development of the laid lines are dependent on the thickness of the splints and threads. A medium-range dehydration rate is probably desirable in order to strike a balance between good sheet formation and efficient operation. To satisfy this requirement, thick cylindrical splints are aligned with relatively wide interspaces (thick threads) and thin cylindrical splints are aligned with relatively narrow interspaces (thin threads) to match the freeness (rapidity of dehydration) of the fibers used. However, when the equivalent total area of the interspaces is considered, narrow interspaces decrease the dehydration rate as compared to fewer wide interspaces. Consequently, for thinner splints, the interspaces should be set relatively wider.

The plant fibers used for papermaking include paper mulberry, *gampi*, and *mitsumata* (*Edgeworthia chrysantha*). If the screen interspaces are too wide, many fibers clog these interspaces during dehydration and appear dense in the dried sheet against backlight. It is predicted that these dense stripes would become clearly visible laid lines. The degree of the clearness or fiber clogging is related to the fiber length, and thus the pitch of the laid lines could be used as data to distinguish between fiber sources. As stated thus far, laid lines of historical documents have a tremendous potential to provide a lot of information about several factors in addition to the wood processing technology that was used to manufacture the screens.

Experimental

Samples

Table 2 shows the contemporary Japanese paper samples that were subjected to the analyses in this work. The fiber sources are *mitsumata* and *gampi*. Screens with splint pitches of 1.21, 1.52, 2.02, and 3.03 mm, or 25, 20, 15, and 10 lines

Table 2. Contemporary Japanese paper samples

Fiber source	Spacing of screen bamboo splints		Attached side in drying	Mean basis weight (g/m^2)	Mean density (g/cm^3)
	Pitch (mm)	Frequency (lines/*sun*[a])			
Mitsumata	3.03	10	Screen	65.1	0.50
Mitsumata	2.02	15	Screen/top	66.4/62.2	0.48/0.46
Mitsumata	1.52	20	Screen/top	57.2/65.8	0.47/0.46
Mitsumata	1.21	25	Screen/top	63.0/64.9	0.49/0.49
Gampi	2.02	15	Screen	73.0	0.64
Gampi	1.52	20	Screen/top	71.4/66.9	0.62/0.64
Gampi	1.21	25	Screen/top	73.8/67.0	0.67/0.63

[a] 1 *sun* = 30.3 mm

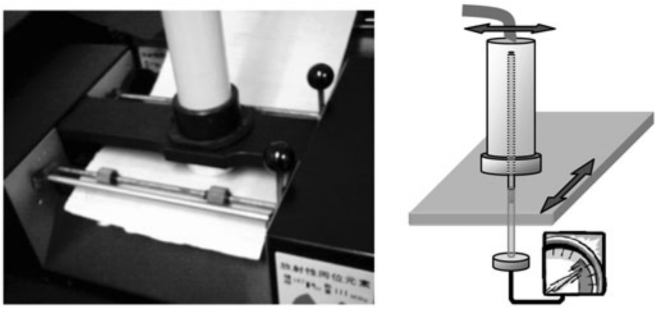


Fig. 4. Beta formation tester and scan directions of paper and beta-ray spot

per *sun*, were manufactured for this work. The side attached to a drying wooden board affects the finish; the board side usually becomes smoother than the other side, i.e., the brush side. This term was based on the brushing operation for spreading a wet sheet out on the drying board. For the beta-ray formation test only, samples prepared under slightly different conditions were used. For reference, the mean length of *kozo*, *gampi*, and *mitsumata* fibers is approximately 6, 5, and 4 mm, respectively.

Analytical methods

First, the basis weight, i.e., the mass per unit area, and the thickness were measured. For thickness measurement, a micrometer was used at 100 kPa, as specified in the ISO 534:2005 standard. Then, density was calculated from the basis weight and thickness.

Second, mass distribution was measured with beta rays using a beta formation tester from Ambertec, Sweden, and with soft X-rays using the PRO-TEST 150 from Softex, Japan. The transmittance of beta rays correlates to the local basis weight, and the transmittance distribution was converted to a basis weight distribution. Figure 4 shows a beam spot diameter of 0.5 mm, and this spot was moved at 1-mm intervals for 10 mm in the direction of the laid lines and for 50 mm in the cross direction to obtain two-dimensional data. Between the samples with different basis weights, the grey level of the images was adjusted such that the same grey level corresponds to the same basis weight. The transmitted soft X-ray images were photographed as well. Soft X-rays are also said to provide a local basis weight distribution from the transmittance data because they are less scattered by porous materials compared to visible light. Therefore, X-ray radiography has been considered in reference to the methods of Bridgman[3] and Aken,[4] and laid lines and watermarks of historic documents have been recorded as one of the properties as presented by Aken,[5] Holle et al.,[6] and Brown and Mulholland.[7] However, scattering was found to adversely affect the correlation when the accelerating voltage supplied to the X-ray tube was approximately 10 kV in our preliminary experiment: a compressed part of a sheet of paper transmitted more soft X-rays than the rest of the sheet. To reduce this adverse effect as much as possible, the accelerating voltage was set between 40 and 60 kV, and the tube current and time of exposure of the X-ray sensitive imaging plate were 1.5 mA and 1–3 s, respectively. The exposed imaging plates were read by an IP reader from Rigaku, Japan. This system has a resolution of 50 µm in the XY direction, although it was difficult to attain a stable output condition and convert the output to a basis weight quantitatively.

Third, the surface profiles were measured with a laser microscope: VF-7500 from Keyence, Japan. The measured area was 2.7 mm (35 pixels) in the laid line direction and 20 mm (256 pixels) in the cross direction. The resolution was 78 µm in the XY direction and 1 µm in the vertical direction.

Lastly, the paper samples were observed with an optical microscope, BX51 from Olympus, Japan, to examine the geometrical surface structure of the laid lines using two-way low-angle illumination in both the laid line direction and the cross direction. This illumination effect emphasizes the edges of those fibers that are aligned only in the perpendicular direction to the illumination. The magnification of the lenses was ×40 (×10 for the eyepiece and ×4 for the objective). Fiber alignment images taken with a digital camera were connected to cover a relatively wide area. The laser microscope was also used to obtain separate paper surface images of low-angle illumination in the laid line direction and the crosswise direction.

Results and discussion

Basis weight and density

Figure 5 shows the fundamental properties such as basis weight and density as a function of the splint pitch of the screens used. The basis weight was almost constant regardless of the pitch for both *gampi* and *mitsumata* fibers. This is because even though the dehydration rate is supposed to be different for screens of different pitches, the abundant experience and excellent technique of the craftsman resulted in the sheets being made with similar basis weights. The apparent sheet density was constant as well, regardless of the pitch for the same fiber source. However, sheets prepared from *gampi* fibers were thinner than those prepared from the other fiber sources and they tended to have higher density – 0.65 g/cm^3 for *gampi* and 0.50 g/cm^3 for *mitsumata*.

Local basis weight (fiber mass) distribution

Figure 6 shows the grey level images of the local basis weight distribution converted from beta-ray transmission. Measurements were made twice for different locations of each sample. The grey level is proportional to the actual basis weight on the same scale for the six images. Periodic stripes can be clearly observed in sample *a* (*mitsumata*, 3.03 mm, top). This stripe pitch agrees with the laid line pitch sensed with transmitted visible light. From this result, we can infer that uneven fiber mass distribution generates laid lines that can be perceived visually. The periodicity of samples *b* (*gampi*, 2.02 mm, screen) and *c* (*gampi*, 2.02 mm, top) is ambiguous, but one can perceive intermittent stripes to some extent. The 1-mm beam spot interval is close to the pitch of these laid lines and could be a cause for the ambiguity. With regard to the variation in the grey level, i.e., the measured unevenness of the basis weight for each sheet, the range between the maximum and minimum values of the local basis weight was 44, 24, and 24 g/m^2 for samples *a*, *b*, and *c*, respectively. This result implies that narrower distributions of the local basis weight are obtained using screens with shorter splint pitches.

The beta formation tester has an instrumental limitation with regard to the beam scan interval and therefore it cannot be set to any value less than 1 mm. Soft X-ray apparatus with a much higher resolution of 50 µm was utilized, although transmitted soft X-ray images cannot be converted to the local basis weight distribution. Figure 7 shows the transmitted soft X-ray images. Periodic stripes were clearly observed with sample *a*, which had a pitch of 3.03 mm, while

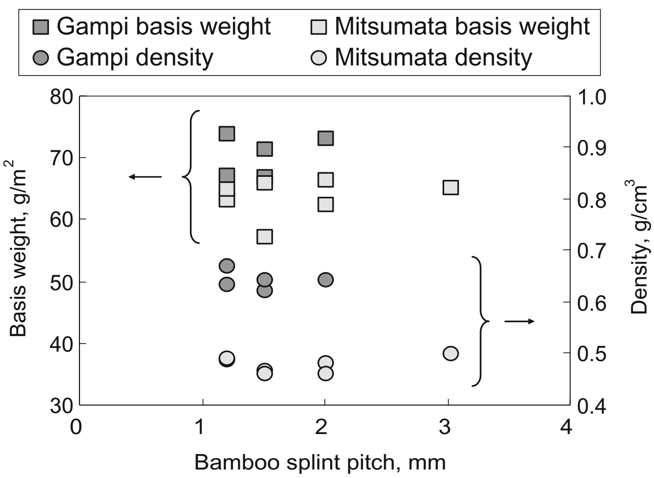


Fig. 5. Basis weight and density of Japanese paper samples prepared from *gampi* and *mitsumata* fibers

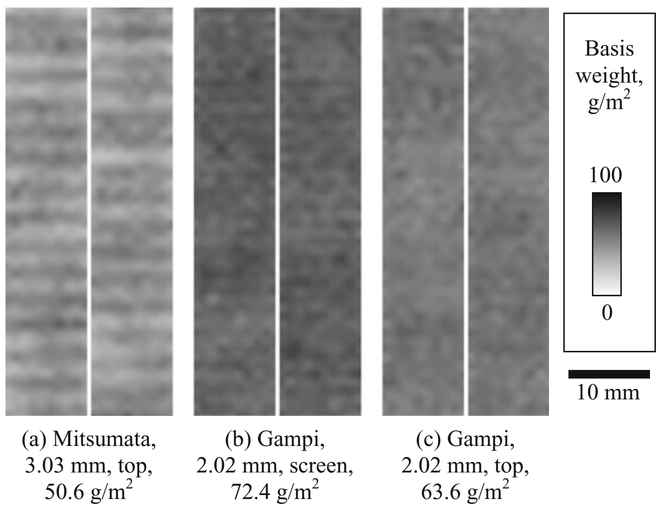


Fig. 6. Images of local basis weight distribution obtained from beta-ray transmission. Sample descriptions (**a–c**) denote the fiber source, splint pitch, and the side attached to the drying board. Two samples were analyzed for each paper type

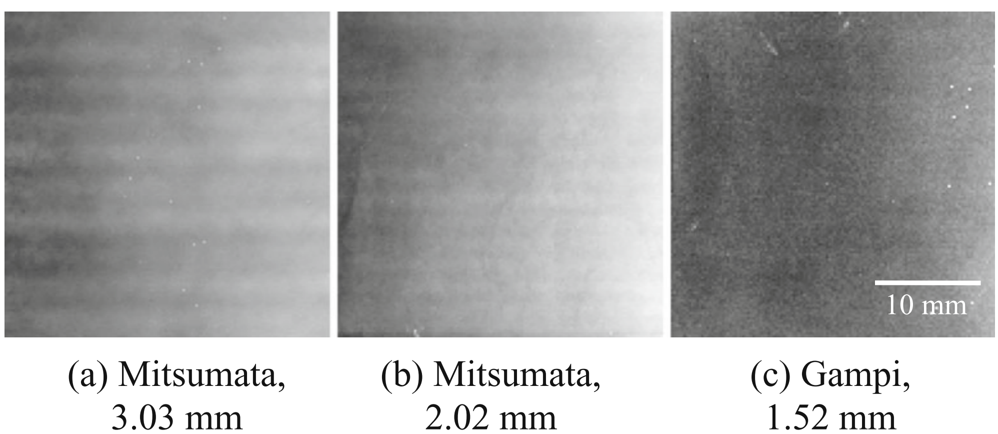


Fig. 7. Transmitted soft X-ray images representing the relative distribution of the local basis weight. The sample descriptions (**a–c**) denote the fiber source and splint pitch

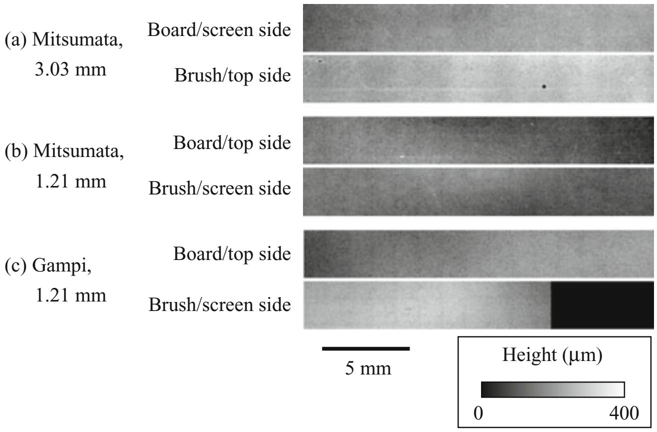


Fig. 8. Surface profile images obtained from a confocal laser microscope. The *right end of the bottommost picture* is completely black because that area lies outside the sample range

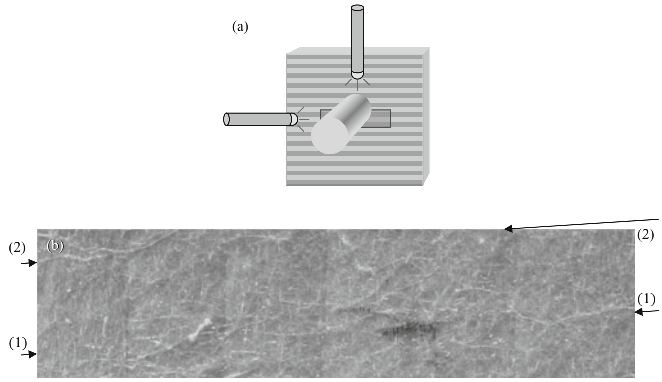


Fig. 9. a Configuration of two-way low-angle illumination and **b** paper surface with only horizontal and vertical fibers emphasized by the illumination. On careful viewing, one can observe that horizontally aligned fibers extend along a line between the two *arrows* denoted *1*. Part of another line consisting of similar horizontally aligned fibers is indicated by *arrows* denoted *2*

those of sample *b*, which had a pitch of 2.02 mm, could be discerned, but less clearly. However, no stripes were observed for sample *c*, which had a pitch of 1.52 mm; the reason for this is not that the pitch is so short that the fiber mass unevenness cannot be recognized because the resolution is high enough for such a pitch to be detected. It was concluded that screens with a splint pitch less than 1.52 mm do not cause fiber mass unevenness even for *gampi* fibers, which are the shortest and thinnest among the popular fiber sources used for Japanese paper.

Surface roughness induced by laid lines

Figure 8 shows the surface profile images measured three-dimensionally, i.e., the distributions of height at each position as grey-scale images. Periodic stripes with a pitch of approximately 3 mm were observed only for the brush side of sample *a* (*mitsumata* 3.03 mm). The pitch of the observed stripes and that of the splints of the screen agree well. However, no stripes were observed on the board side. Further, no stripes were observed on either side of the other two samples *b* and *c*, each having a pitch of 1.21 mm. In short, when the pitch is long, the clear appearance of laid lines due to fiber mass unevenness includes the periodic pattern of surface roughness with the same pitch, i.e., pattern (a) of A in Table 1 is obtained. Interestingly, although the fibers clog the interspaces between the splints and protrude above the surface plane of the screen side in the forming process, the protruding fibers are pushed over to the brush side surface while drying on the board. The images of the two samples *b* and *c* with a 1.21-mm splint pitch did not reveal such a periodic roughness. In fact, slight periodic roughness may be present, but it is probably hidden by the macro roughness that is induced by poor sheet formation irrespective of the laid lines. Perfectly periodic stripes with a pitch of approximately 1.3 mm observed especially with the samples on a screen having a pitch of 1.21 mm are artifacts caused by the connection of small images with different gray levels on left and right sides to construct wide images. Even for very smooth surfaces, such stripes are observed and they are not related to the laid lines.

Laid lines visualized by reflected light

From the results of fiber mass distribution and surface profile, we make the following observations. When the splint pitch is sufficiently long, laid lines can be perceived against backlight due to the uneven distribution of fiber mass arising due to the surface roughness caused by fibers clogging the splint interspaces. As the pitch becomes shorter, the laid lines can be discerned faintly. However, this is not because the pitch is too short for the resolution of the human eye, but because there is even distribution of the fiber mass and surface roughness because of the absence of fiber clogging. Therefore, the laid lines observed by diffuse reflected light are assumed to be developed by a mechanism other than fiber mass unevenness or surface roughness.

Considering this assumption, optical microscopic observations were conducted using low-angle illumination, as shown in Fig. 9a. Figure 9b is an image composed from separate small images. Horizontally aligned fibers are emphasized because the illumination from the top of this image was slightly stronger than that from the left side. On paying careful attention, one can observe that horizontally aligned fibers extend along a line between the two arrows denoted by (1). The black pencil mark located towards the right from the centre of the image was placed exactly on the laid line when the sheet surface was viewed with diffuse reflected light so that the pencil mark was longer in the longitudinal direction of the laid line. The horizontal fibers appear to extend exactly along this laid line. Next to this line across a short space, a part of another line consisting of similar horizontally aligned fibers is observed, as indicated by arrows (2). The characteristic alignment of such fibers cannot be observed until the surface is illuminated from a direction perpendicular to the laid lines at a low angle. These fibers would not be recognized by illumina-

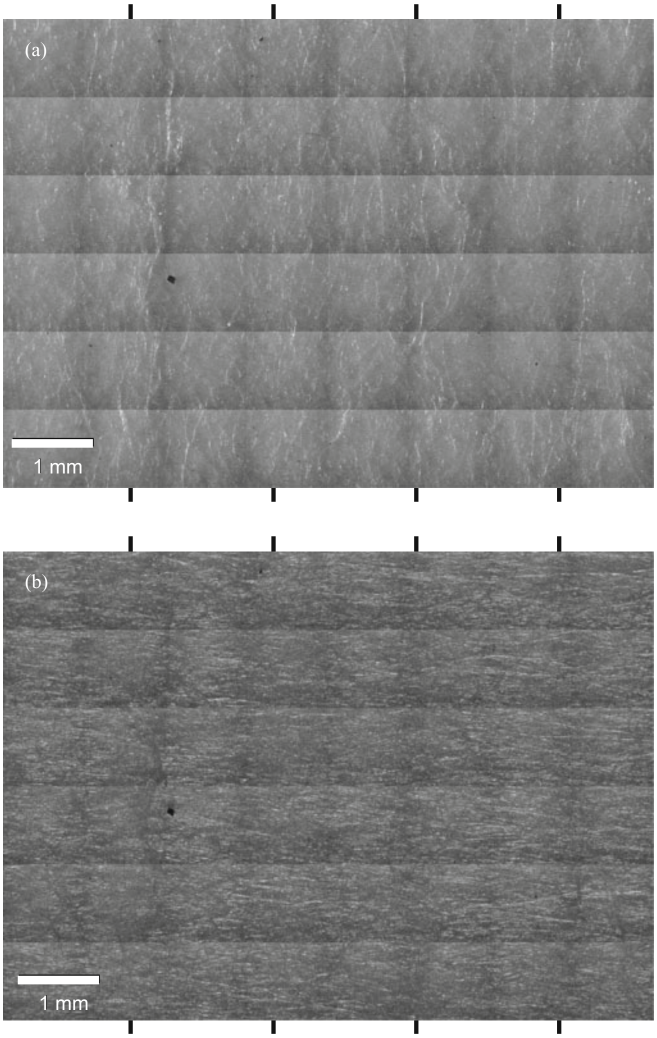


Fig. 10. Micrograph of a paper surface illuminated from the left (**a**) and bottom (**b**) at a low angle to emphasize the fibers aligned in the vertical and horizontal directions, respectively. The locations are exactly the same

tion from all directions used regularly to prevent uneven illumination.

In flow sheet forming, the fiber orientation of the screen side surface always occurs in a direction perpendicular to the laid lines, as our previous work proved.[3] As an exception, many fibers on the laid lines are oriented parallel to the laid lines, as seen in the present work. However, this apparent contradiction is logically resolved by the fact that those oriented fibers are covered with major cross laid-line fibers. Figure 10 shows images in which the fibers are emphasized by illuminating the left and bottom side, respectively. There appear to be a lot of cross laid-line fibers even on the laid lines. In other words, the real first surface layer has fibers oriented in the cross laid-line direction; this is because immediately after a strong shaking action, the fiber suspension on the screen flowed in the cross-splint direction such that the flow stream of the fibers is faster than the dehydration stream. Figure 11 depicts the order of the layer formation. From the screen side surface of the sheet, the

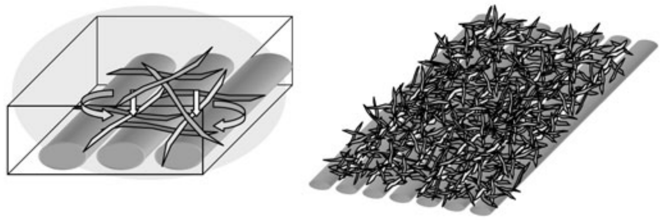


Fig. 11. Schematic of fiber orientation generation. The fibers are oriented in the cross bamboo splint direction in the first layer (*red fibers*) and oriented in the bamboo splint direction in the second layer (*blue fibers*), followed by the less oriented bulk layer (*brown fibers*)

cross laid-line direction-oriented layer, parallel laid-line direction-oriented layer, and less oriented layer are formed in this order. In paper, fibers tend to reflect more light in their longitudinal direction and thus when fibers are irradiated by light in a direction that is almost parallel to the laid lines, the fibers in the parallel laid-line direction-oriented layer reflect more light. However, illumination set to 45º provides a good contrast to recognize the laid lines readily because the fibers in the cross laid-line direction reflect much less light. In the constant illumination condition, the laid lines alternately appear clear and unclear and sometimes the density of the contrast is reversed when the sheet of paper is rotated gradually in the sheet plane. These phenomena can be explained by the dependence of angular reflectivity on the fiber orientation, or in other words, by the mechanism that the reflected light intensity is altered by the azimuthal angle of illumination relative to the laid line direction. This mechanism may apply to the case of long splint pitches as well, but uneven fiber mass distribution and surface roughness probably hide the angular reflectivity due to the fiber orientation.

The mechanism of the perception of laid lines proved in this work is merely one of many patterns of visibility. Understanding other mechanisms such as brown discoloration of some additive or component concentrated on the laid lines is necessary as future work.

Conclusions

Laid lines can be visually perceived in Japanese paper. They can be observed against backlight because fiber mass distribution occurs within a sheet. In addition, surface roughness is present in accordance with the laid lines. However, if the splint pitch is shorter than approximately 2 mm, the laid lines can be observed only with reflected light and cannot be observed against backlight. In this case, there is no fiber mass distribution, but the laid lines are related to fiber orientation. In the flow sheet-forming method, the fibers become oriented strongly in the cross-splint direction in the first layer, probably due to the fact that the flow stream of the fibers is faster than the downward dehydration stream. Subsequently, the fibers rotate and become aligned along the interspaces between the splints during dehydration. Bidirectionally oriented fibers perpendicular to each other result in a contrasting reflectivity and the laid lines are visible only with reflected light because the oriented fibers reflect more light in the longitudinal direction.

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References

1. Inaba M (2004) New conservation techniques for paper (in Japanese). Sen'i Gakkaishi 60:443–444
2. Kato M, Shoji T, Murayama K, Okada Y, Enami K, Ikeda K, Sakata M (2003) Development of measurement method to count laid lines and its application (in Japanese). In: The 25th research conference proceedings. The Japan Society for the Conservation of Cultural Property, Kyoto, pp 70–71
3. Han Y-H, Enomae T, Isogai A, Yamamoto H, Hasegawa S, Song J-J, Jang S-W (2006) Traditional papermaking techniques revealed by fiber orientation in historical papers. Stud Conserv 51:267–276
4. Bridgman F (1965) Radiography of paper. Stud Conserv 10:8–17
5. Aken J (2003) An improvement in Grenz radiography of paper to record watermarks, chain and laid lines. Stud Conserv 48:103–110
6. Holle H, Leitner K, Schreiner M (2006) The Determination and interpretation of watermarks in graphic art objects of the seventeenth century. In: The object in context: Contributions to the 2006 IIC Congress, Munich, pp 321–321
7. Brown A, Jean E, Mulholland R (2002) Using microfocus X-radiography and other techniques to create a digital watermark database. In: Works of art on paper: books, documents and photographs, techniques and conservation: Contributions to the 2002 IIC Congress, Baltimore, pp 21–26