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Analysis of Cotton Maturity Degree on Microstructure Level by Fuzzy Set Conception

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Abstract
This paper is a continuation and generalisation of an earlier study of cotton maturity degree determination in the earlier paper. Up till now the maturity degree of cotton has been determined by the analysis of longitudinal outside views of cotton fibres. Early, we proposed a method of cotton maturity determination based on SEM images of cotton fractures. Fuzzy set conception was adopted to analyse each image, considering the fracture category. In this paper have emphasized the fuzzy aspects of cotton maturity determination by analysing the longitudinal outside views of cotton in accordance with the "Russian-standard", and by using a new method for determination, which is based on analysing SEM images of cotton fractures proposed by as.

Key words: *similarity measure, cotton fracture, maturity degree.*

Introduction

The industrial utility of cotton textiles depends among others on the cotton maturity degree. The cotton maturity degree is a parameter influencing the process of cotton spinning. Complex forces such as: tensile, bending, twisting and friction forces act on the cotton filament during spinning. A single fibre's reaction to these forces depends on its maturity degree. The best fibres for the spinning process are cotton with a maturity degree of 2.0 to 3.0. Cottons with a maturity degree lower than 1.5 and over 3.5 are not good for spinning; as they undergo damage during spinning. The stiffness of these cottons is too low or too high. The maturity degree is therefore an important parameter for the prediction of textile properties.

Until now, the maturity degree of cotton fibres has been determined in several ways, such as the method of polarised light, the method of light absorption, the bubble method, the Advanced Fibre Information System (AFIS) and the method using Sonic Fineness Tester apparatus [2 - 4]. But the most common methods for maturity degree determination consist of the analysis of longitudinal outside views of cotton fibre at a macro scale [5, 6]. This method, called "Russian-standard" or "Soviet-standard", is also the basis of the Polish standard.

A new method of determining the maturity degree of cotton based on the examination of cotton fractures by using a scanning electron microscope (SEM) technique and fuzzy set theory is proposed by us. Images of cotton fractures are very diverse depending on its microstructure and maturity degree. This method of maturity determination, signalised and briefly described in [1], is systematically presented in this article [1)].

Standard method of determining the maturity degree of cotton

Using the standard method, an expert must compare longitudinal outside views of cotton with a pattern characteristic for each maturity degree. These patterns are shown in Figure 1. The standard method distinguishes eleven discrete values of maturity degrees: 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, and 5.0. In practice, the lower and higher values (0.0; 4.0; 4.5; 5.0) do not occur, and we omit them, denoting the set of standard maturity degree values as:

$$X : [x_1, ..., x_7] \qquad (1)$$

Where: $x_1 = 0.5$, $x_2 = 1.0$, $x_3 = 1.5$, $x_4 = 2.0$, $x_5 = 2.5$, $x_6 = 3.0$, $x_7 = 3.5$.

In order to determine the maturity degree, an expert must discriminate such properties of the longitudinal views of fibres as:

- the transparency of fibre,
- the width of fibre,
- the bend of fibre,
- the character of twist (short or long),
- the number of twists of fibre.

These features must be compared by an expert with the drawing patterns such as in Figure 1. Based on the results of such a comparison, the maturity degrees of cotton fibres are determined. It is obvious that this comparison is not completely precise the maturity degrees are, to some extent, subjectively evaluated, and we may introduce the fuzzy set conception in this cotton maturity classification.

Let us denote, in turn, the above properties of the longitudinal views of fibres as a set:

$$Z : [z_1, z_2, z_3, z_4, z_5] \qquad (2)$$

Each of the Z features appears to some extent. We assume the numerical interval [0,1] to evaluate the appearance of the above features, based on the rule:

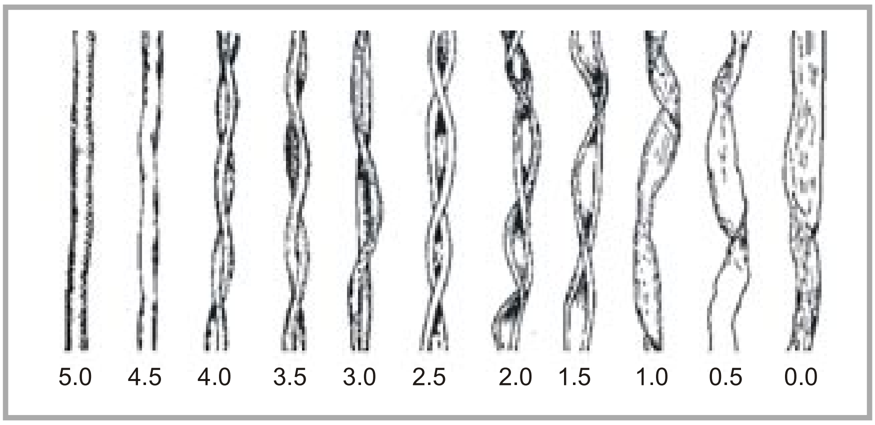

Figure 1. *Standard maturity degree.*

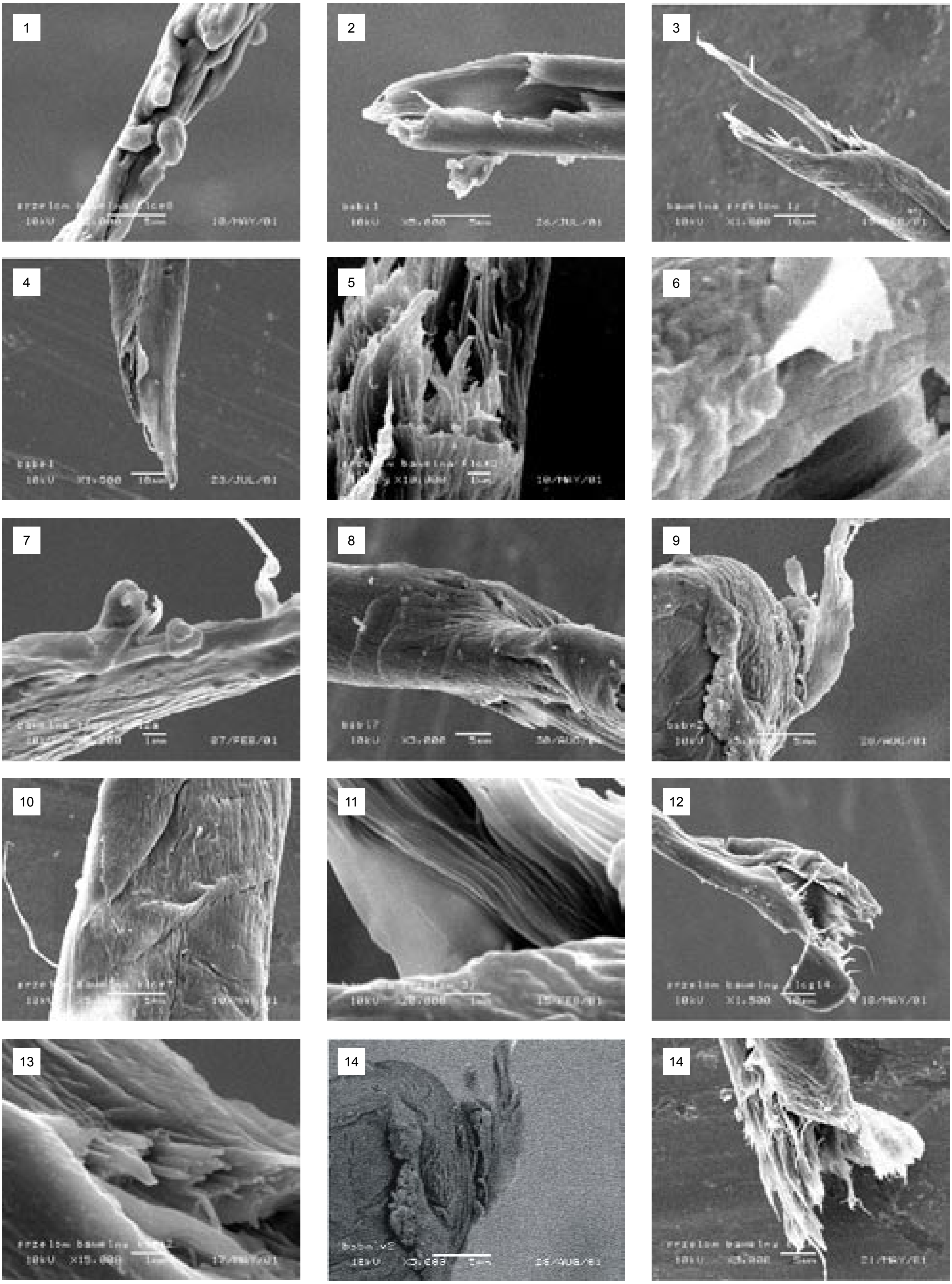

Figure 2. *Category of cotton fracture, visible on the SEM images, and number of category (in brackets): stretched rubber (1), broken tree (2), cracked untwisted rope (3), cohesion of broken fibre end (4), macro- and micro-fibrils occurring in the broken fibre end (5), ductile callosities (6), shapeless agglomerate (7), folds (8), wrinkles (9), furrows (10), grooves (11), stratification of morphological fibre structure (12), appearance of fibril structure, primary wall (13), brush shape (14).*

z_1 – transparency of fibre: 1- transparent; 0.5 - partially transparent; 0 - not transparent.
z_2 – width of fibre: 1 - wide fibre; 0.5 - "transitional" fibre; 0 - narrow fibre.
z_3 – bend of fibres: 1 - existing; 0.5 - existing in the form of fold; 0 – lack.
z_4 – character of twist: 1- existing long twists; 0.5 - existing long and short twists; 0 - existing short twist.
z_5 – number of twist: 1 - many numbers of twist; 0.5 - twist begins to occur; 0 - lack of twist.

Assigning each longitudinal view of cotton in this way, a number from the interval [0,1] is indeed the generation of a fuzzy relation [9,10]. This relation may be formally written in the form:

$$\Phi = \{\varphi(x_i, z_k), \forall (x_i, z_k) \in \Omega \mid \varphi : \Omega \rightarrow [0,1] \qquad (3)$$

where: $x_i \in X, z_k \in Z$; $\Omega = X \times Z$ is the Cartesian product of set *X* and *Z*; φ - membership function of fuzzy relation Φ [10].

In this way one may create, based on the patterns of Figure 1, a fuzzy relation Φ which constitutes a fuzzy pattern to evaluate the cotton maturity degrees. Such a fuzzy pattern is in accordance with the "Russian-standard", formally called "Soviet-standard" (Figure 1) and is presented in Table 1. The values of membership function φ characterise the appearance of the given features of the longitudinal view of cotton.

In order to determine the maturity degree of the cotton analysed, according to the above-mentioned fuzzy relation Φ, the longitudinal view of cotton must be characterised and assigned a suitable number from the interval [0,1] for each Z feature. In this way a new fuzzy relation Ψ will be generated, which characterised the cotton maturity analysed.

Comparison of the relations Φ and Ψ enables us to determine the maturity degree in accordance with the "Russian-standard". This comparison is based on a similarity measure of fuzzy sets [10] and Zadeh`s logical sum notation [9] of fuzzy sets. This method is presented in the subsequent considerations in this paper.

Fuzzy maturity degree

SEM images of cotton fracture

Investigations into the properties of cotton fibres include the analysis of their microstructure. Images of the cotton fracture are a valuable source of knowledge regarding its microstructure.

In order to receive an image of cotton fracture, which would enable its useful evaluation, we had to perform the following experiment. Each single cotton fibre was glued in a paper frame with a jamming dimension of 1 cm. After that, the single cotton fibre was tensile stretched almost to break. The end of the broken fibre was mounted on a carrier stub, using silver glue. The samples were covered with gold by a JFC 1200 Joel ionic spatter, so the fracture samples preparaed were observed by the scanning microscope and fracture images were received.

Detailed analysis of cotton fracture images enable us to discriminate 14 different, general categories of the fractures presented in Figure 2 [3]. Each category of fracture SEM image was classified with a verbal description:

- Category 1: 'stretched rubber'. This image is characterised by large plasticity. The piece of end fracture represents a smooth surface, the spherical objects on the fragment of the broken end are not folded. A lack of visible folds and grooves can be observed.
- Category 2: "broken tree". The broken end has not so much a ductile shape, the break is more 'dry', furrows and grooves begin to appear.
- Category 3: "cracked untwisted rope". The broken end is reminiscent of a broken and untwisted rope. The structure of the cotton fibre appears to be an arrangement of macro- and microfibril-like twisted rope. The image characterises elasticity features, and in consequence the samples partially untwisted.
- Category 4: "cohesion of broken fibres". An image of the microstructure of broken fibres characterised by relatively large cohesion. The untwisted end of the broken fibre consists of only 'ribbons of fibres', but not of a fibril structure.
- Category 5: "occurrences of macro and micro fibrils in the broken-fibre end". This image of microstructure cotton fracture presents longitudinal splitting, occurring during the process of tearing the structure. This macro – fibril structure proves that the cotton is riper and has a higher maturity degree.
- Category 6: "ductile callosities". This image of cotton fracture shows big ductile callosities. The structure is plastic and during tearing grows thicker.
- Category 7: "shapeless agglomerate". This image of cotton fracture contains both plastic and elastic features. Spherical agglomerates reminiscent of stretched and deformed rubber are visible, as well as furrows, grooves and bunches of fibrils.
- Category 8: "folds". This image of broken cotton fibre presents folds situated in the neighbourhood of the end of fibre fracture. These folds indicate that the cotton microstructure is differentiated along its cross section. The cotton consists of structurally different layers. These layers behave in a different manner during deformation.
- Category 9: "wrinkles". This image of cotton fracture presents a broken end. On this image the exposed layer of the primary wall is visible; the cuticle layer has actually been removed. This testifies that distinct structural differences between the cuticle layer and deeper layers exist.
- Category 10: "furrows". This image of cotton fracture presents furrows formed on the cotton surface in the neighbourhood of the end fracture. These furrows arise in the tearing process. It testifies that deeper layers are more crystalline than external

Table 1. *Fuzzy pattern in accordance with the "Russian-standard".*

Maturity degree		Transpa rences z_1	Width of fibre z_2	Bend of fibre z_3	Charac ter of twist (Short orLong) z_4	Number of twists of fibre z_5
x = 0,5	Immature Fibres I	1	1	1	0	0
x = 1,0		1	1	0,5	0	0
x = 1,5		0,5	0,5	0,5	0	0
x = 2.0	Not mature fibres II	0	1	0,5	0,5	0,5
X = 2.5		0	0,5	0	0,5	1
X = 3.0	Mature fibres III	0	0,5	0	1	0,5
x = 3.5		0	0	0	1	1

layers with respect to the maturity degree. Superficial layers are more amorphous and undergo deformation more easily.

- Category 11: “grooves”. This image of cotton fracture presents micro grooves, which are visible in the fracture. These grooves testify that microfibrils appear. The secondary wall layer is so crystalline that microfibrils are visible. The microfibrils of the broken end of the fibre do not lose cohesion, and cotton splitting does not occur.
- Category12: “stratification of morphological fibre structure”. This image of cotton fracture presents the stratification of morphological elements. The cuticle layer is removed from the fracture and the primary wall with fibrils is visible. With each layer possessing such a character of fracture, this highlights the large differentiation of superstructure. The parameters of cotton superstructure, the index of crystallinity, the size of crystallites and the texture are changed.
- Category 13: “appearance of fibril structure”. This image of cotton fracture presents longitudinal splitting of the microfibrilar structure of cotton. It highlights the large crystallinity index of microfibrils and high cotton maturity degree. This gives a large elasticity effect and single fibrils are visible at the broken end of the fibre.
- Category 14: “brush shape”. This image of cotton fracture presents the brush end of the fracture. All the layers of cotton microstructure are crystalline enough, which produces the splitting effect of the fibre fracture.

We denote the above categories of cotton images, described verbally in Table 2, as a set:

$$Y : [y_1, ..., y_{14}] \quad (4)$$

Where y_1, ..., y_{14} are images characteristic for cotton microstructure, identified during visual observation.

Table 2. *Categories of SEM images of cotton fracture.*

Numb of category	Category
Y_1	Stretched rubber
Y_2	Broken tree
Y_3	Cracked untwisted rope
Y_4	Cohesion of broken fibre end
Y_5	Occurrence of macro- and micro-fibrils in the break fibre end
Y_6	Ductile callosities
Y_7	Shapeless agglomerate
Y_8	Folds
Y_9	Wrinkles
Y_{10}	Furrows
Y_{11}	Groves
Y_{12}	Stratification of morphological fibre structure
Y_{13}	Appearance of fibril structure
Y_{14}	Brush shape

Cotton maturity as fuzzy relation

It is postulated here that the character of the fracture image depends on the maturity degree and may be described by the concept of fuzzy set theory.

These categories are discriminated by visual characterization of images (see Figure 2, page 14) and are denoted verbally (see Table 2), and they may also be a basis for maturity degree determination. The procedure for fuzzy maturity determination is presented in Figure 3.

We assume that for each cotton fibre of the population analysed (1 - Figure 3), the maturity degree had been previously determined using the method with fuzzy relation Φ, as described (2 - Figure 3), and that the population of the cotton analysed included representatives of each maturity degree.

For these cotton populations we carried out the following experiment. Cotton fibres were tensile stretched with the use of an Instron Tensile Tester and for each fracture (3-Figure 3) SEM microphotographs were taken (4 - Figure 3).

We previously distinguished 14 category images of cotton fractures (Figure 2 and Table 2) as a result of discrimination of the elements of cotton microstructure visible on SEM images (6 - Figure 3). These categories specify the fracture images with not entirely sharp boundaries: the differences between each category are not completely distinct.

In order to form a fuzzy standard relation, each of the 14 category images of the cotton population prepared earlier should be identified. One must visually estimate, for each of the 14 category pattern fracture images, its occurrence in the population of images received earlier. This identification of image category is ambiguous because of the not explicit details which discriminate each of images. The fuzziness of the image category identification should be understood as a subjective gradation of certainty that the

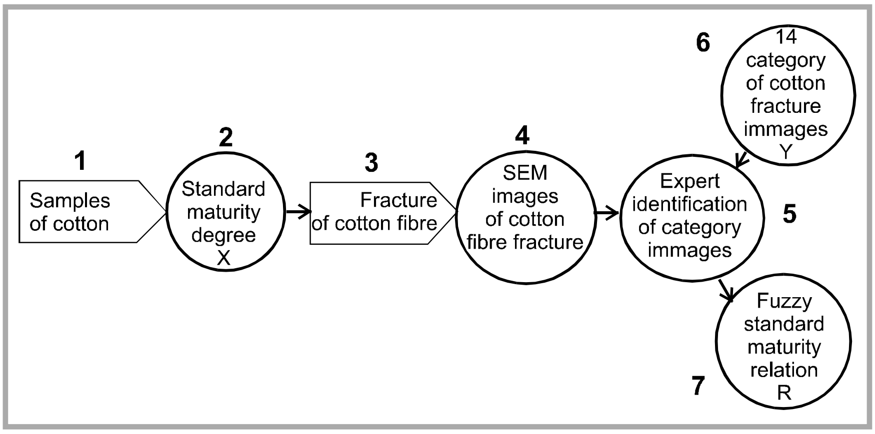

Figure 3. *Procedure for determination of fuzzy standard maturity.*

Table 3. *Discrete membership function values for SEM image cotton fracture [1].*

Maturity degree	Number of category													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Plastic fracture				Elastic – plastic fracture				Elastic fracture					
0.5	1	0.5	0.5	0.5	0	1	0.5	0	0	0	0	0	0	0
1.0	1	1	1	1	0	1	1	0.5	0.5	0	0	0	0	0
1.5	0.5	1	1	1	0.5	1	1	1	0.5	0.5	0.5	0	0	0
2.0	0.5	0.5	0.5	1	1	0.5	1	1	1	1	1	0.5	0.5	0.5
2.5	0	0.5	0.5	0.5	1	0.5	0.5	0.5	1	1	1	0.5	0.5	1
3.0	0	0	0	0	1	0	0	0	1	1	1	1	1	1
3.5	0	0	0	0	0.5	0	0	0	0.5	0.5	0.5	1	1	1

image of the given fracture belongs to the given maturity degree.

Therefore the values of the membership function (for each of the given maturity degree) were determined according to the following procedure:

1. N images of cotton samples are given for each x_i, where $i \in [1, 2, ..., 7]$ and x_i - previously determined 'Russian-Standard' maturity degree.
2. If y_j category, (according to expert valuation) occurs n times in the N-sample population of x_i maturity degree, then the frequency of its occurrence is $\alpha_{i,j} = n/N$.

For fuzzy valuation of the category occurring in the sample population, we apply the "gate rule":

- if $\alpha_{i,j} < 0.25$ then $f(x_i, y_j) = 0$
- if $\alpha_{i,j} > 0.75$ then $f(x_i, y_j) = 1$
- if $0.25 < \alpha_{i,j} < 0.75$ then $f(x_i, y_j) = 0.5$; $i \in [1, 2, ..., 7], j \in [1, 2, ..., 14]$

These numbers are matched by an expert as discrete values from the interval [0, 1] and may be interpreted as values of the membership function according to Zadeh`s fuzzy set conception [7, 8, 12]. The membership value "1" is assigned when the category y_j evidently occurs in the samples of the given maturity degree x_i, whereas value "0" is valid in the opposite case. The value "0.5" is assigned to an intermediate state, which means that the category y_j ambiguously belongs to the given maturity degree x_i.

Fuzziness should be understood as a subjective gradation of certainty, that the category y_j belongs to a given maturity degree x_i. In Table 3 membership function values received by an expert, according to the above-mentioned procedure are written down.

On the basis of the sets X and Y, we denote a Cartesian product as: $\Gamma : X x Y$. Let us now define the fuzzy relation R as:

$$R = \{f(x_i, y_j) | (x_i, y_j) \in \Gamma | f : \Gamma \to [0,1]\} \quad (5)$$

The membership function $f(x_i, y_j)$ of the fuzzy relation $R(x_i, y_j)$ assigns a number (0, 0.5 or 1) to every pair, as is shown in Table 3. The membership function values characterise the membership of each pair of "image category – maturity degree" to the fuzzy relation R (7-Figure 3). Fuzzy relation R is interpreted as the "micro scale pattern" evaluation maturity degree, compatible with the "Russian – standard" also PN standard.

The values of the membership function $f(x_i, y_j)$ of the fuzzy relation R are illustrated in Figure 4. In Figure 4 the relation R is spatially extended. For these purposes the Kriging method was applied [13, 14]. Kriging is a geostatistical method which produces a visually appealing contour and surface plots from irregularly spaced data a Surfer program [15] was applied for spatial girding calculation of the fuzzy relation R by the ordinary Kriging method. The contours in Figure 4 link the points of the same value of the membership function of fuzzy relation R. The contours configuration shows the distribution of the membership function with respect to the image category and maturity degree. The regions of the most occurring values of the membership function of fuzzy relation R are clearly visible.

Determination of cotton maturity by fuzzy relation R_x

The above formed fuzzy relation R of the maturity degree, enables us to evaluate the maturity degree of newly examined cottons. We will now distinguish a discrete representation of the fuzzy relation (5). Using Zadeh`s logical sum notation [10] we can state that:

$$A_i = R|_{x_i} = f(x_i, y_1)|y_1 + ... + f(x_i, y_{14})|y_{14} \quad (6)$$

The fuzzy set A_i is a fuzzy representation of fuzzy relation R for the maturity degree, where $x_i \in X$. Therefore, every x_i maturity degree of cotton has a representation A_i of category pattern.

In order to assign a maturity degree to newly examined cotton fibres, we should identify its cotton fracture microphotographs images with the categories as in Figure 2.

One must assign the values of the membership function $\zeta(x_i, y_j)$ to each SEM image with regard to each y_j category (Figure 2).

Therefore, the fuzzy set B is generated:

$$B = \xi(x, y_1)|y_1 + ... + \xi(x, y_{14})|y_{14} \quad (7)$$

where: $x \in X$.

For maturity determination of the cotton analysed, we can now establish a similarity between sets A_i and B.

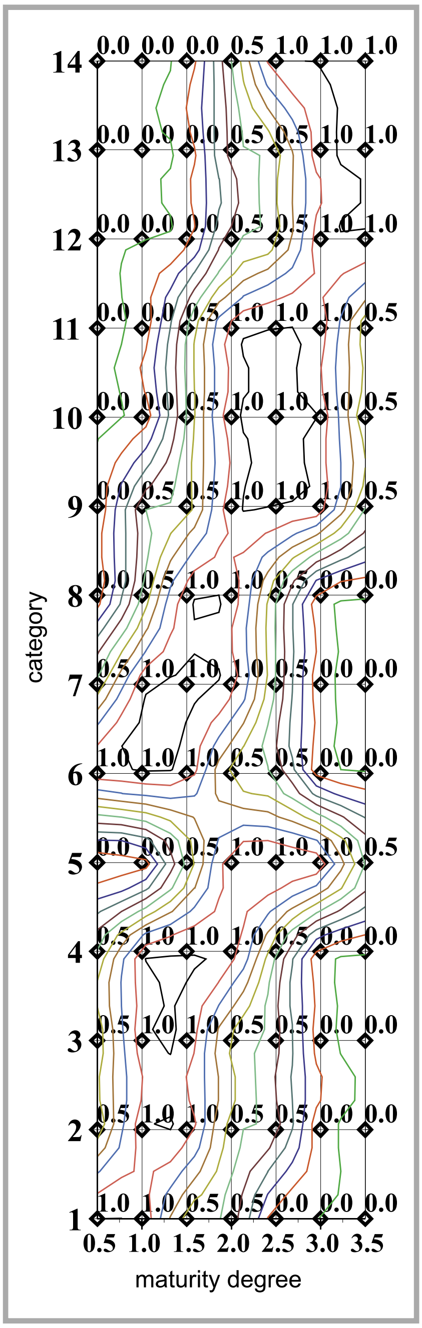

Figure 4. *Correlation between the category of cotton fracture and the membership function, for cotton with different maturity degrees.*

A measure of similarity fuzzy sets A_i and B is defined as follows [9, 10]:

$$S_i = \frac{|A_i \cap B|}{|A_i \cup B|} \quad (8)$$

Where: $|A_i \cap B|$, $|A_i \cup B|$ denote responsible relative cardinality of conjunction and sum of fuzzy sets [8, 9]. Relative cardinality of conjunction $A_i \cap B$ denotes:

$\|A_i \cap B\| = \frac{|A_i \cap B|}{|Y|}$, where $|A_i \cap B|$ is a power of conjunction of A_i and B sets, $|Y|$ - set cardinality. The power of the fuzzy set (for example B) is

$$|B| = \sum_{j=1}^{14} \xi(x, y_j).$$

It is easy to prove that the similarity measure has the following properties:

1. $S_i(A, B) = 0$ if $A \cap B = \phi$
2. $S_i(A, B) = 1$ if $A = B$
3. If $A \supset B \supset C$ then $S(A, B) > S(A, C)$

In order to assign a maturity degree to newly examined cotton, we should determine the value of the similarity measure S_i for each fuzzy subset A_i, $i = [1, 2, ..., 7]$ and B in turn. We receive a sequence of S_i values: S_1, S_2, S_3, S_4, S_5, S_6, S_7. The supreme value $\sup_i \{S_i\}$ of similarity measures designates the maturity degree of the cotton investigated.

Numerical example

Take a fuzzy set B of maturity degree for the cotton analysed:

$$B = 0.1/1 + 0.6/2 + 0.6/3 + 0.4/4 + 0.4/5 + 0.2/6 + 0.5/7 + 0.2/8 + 0.2/9 + 0.8/10 + 0.7/11 + 0/12 + 0/13 + 0.3/14$$

Set B is a logical sum of pairs in which the first element denotes the membership function value of participation of the category fracture to the image of the cotton fracture analysed. The second element is the category fracture number (see Table 1).

We recall a standard discrete representation of fuzzy relation (3) as set A_i, $i = 1$, (see Table 2 and formula 4):

$$A_1 = 1/1 + 0.5/2 + 0.5/3 + 0.5/4 + 0/5 + 1/6 + 0.5/7 + 0/8 + 0/9 + 0/10 + 0/11 + 0/12 + 0/13 + 0/14$$

Let us now calculate the similarity index of fuzzy set A_1 and B

$$S_1 = \frac{\|A_1 \cap B\|}{\|A_1 \cup B\|}$$

The conjunction of fuzzy set A and B is:

$$A_1 \cap B = 0.5/1 + 0.5/2 + 0.5/3 + 0.4/4 + 0/5 + 0.2/6 + 0.5/7 + 0/8 + 0/9 + 0/10 + 0/11 + 0/12 + 0/13 + 0/14$$

The relative cardinality of conjunction $A_1 \cap B$ is:

$$\|A_1 \cap B\| = (0.5 + 0.5 + 0.5 + 0.4 + 0.2 + 0.5)/14 = 2.6/14$$

In an analogical way we calculate the relative cardinality of the sum of fuzzy sets A_1 and B.

$$A_1 \cup B = 1/1 + 0.6/2 + 0.6/3 + 0.5/4 + 0.4/5 + 1/6 + 0.5/7 + 0.2/8 + 0.2/9 + 0.8/10 + 0.7/11 + 0/12 + 0/13 + 0.3/14$$

$$\|A_1 \cup B\| = (1 + 0.6 + 0.6 + 0.5 + 0.4 + 1 + 0.5 + 0.2 + 0.2 + 0.8 + 0.7 + 0.3)/14 = 6.8/14$$

Therefore, the similarity index of A_1 and B is: $S_1 = \frac{2.6}{6.8} = 0.684$

Identically, we calculate: $S_2 = 0.359$, $S_3 = 0.473$, $S_4 = 0.485$, $S_5 = 0.453$, $S_6 = 0.240$, $S_7 = 0.223$.

The sum of S_i is:

$$\sup_i \{S_1, S_2, S_3, S_4, S_5, S_6, S_7\} = S_1$$

The similarity index has a maximum value for set A_1. It means that the maturity degree of the cotton analysed is equal to 0.5.

Summary

- Images of cotton fractures may be not only a source of information of cotton microstructure, but also may be useful for maturity degree determination.
- The method proposed enables us to determine cotton maturity degree on the basis of SEM images of fibre fractures.
- For a given cotton population the maturity degrees were firstly established in accordance with the so called "Russian - standard", using the fuzzy relation Φ.
- The cotton population identified was the basis for determining the maturity degree as a fuzzy relation R, with membership function values of the fuzzy relation R, which were evaluated for SEM images of cotton fracture and subsequently assigned a category.
- It seems that this method should be an appropriate tool for evaluation of the maturity degree when SEM cotton fracture images are available.

- The method of analysis of SEM images with application of fuzzy set elements enables to perform quantitative analysis of cotton fractures images. The method presented enriches the methods of maturity determination so far developed.

Editorial note

1. After publishing the article 'Applying Notions and Methods of Fuzzy Set Theory to Analysis of Microstructure of Cotton Fracture' written by E. Sarna, A. Włochowicz, M. Sarna [1] we have received several questions concerned with the peculiarities of this method. Therefore we have decided to publish this article without shortage, notwithstanding that some fragments have been published in [1]. We hope that the rules of this method are now fully understandable.

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