# Analysis of the surface roughness of woven fabrics

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**Original scientific paper****

*This paper analyzes the surface roughness of woven fabrics as a complex structural property arising from the interaction of constructional parameters, weave geometry, and the orthotropic nature of the woven structure. Special emphasis is placed on the objective quantification of roughness profiles in different measurement directions and on the interpretation of the obtained results in the context of structural symmetry and the diagonal geometry of fabrics. The experimental part was conducted using the Fabric Touch Tester (FTT), where seven woven fabrics with different weave types (plain, basket, rib, twill, and satin) were analyzed. All fabrics were produced from the same cotton yarn to eliminate the influence of raw material parameters. Measurements were performed in the warp direction (0°), weft direction (90°), and in rotated directions (45° and 135°), enabling the analysis of orthotropic behavior of surface roughness. The obtained raw profiles were further filtered and statistically processed, and roughness was quantified using the root mean square deviation parameter Rq. The results show that, despite the orthotropic nature of fabrics, surface roughness does not exhibit strictly orthotropic behavior. The highest Rq values were observed in the diagonal direction of 45° for all analyzed samples, regardless of weave type. Polar diagrams further confirm that structurally symmetrical weaves do not guarantee symmetrical distribution of roughness profiles. The obtained results highlight the necessity of multidirectional roughness measurement and indicate the limitations of interpreting surface properties exclusively in the principal construction directions.*

***Keywords:*** *woven fabric; surface roughness; weave types; orthotropy*

**Izvorni znanstveni rad****

## Analiza hrapavosti površine tkanina

*U radu se analizira površinska hrapavost tkanina kao složeno strukturno svojstvo koje proizlazi iz međudjelovanja konstrukcijskih parametara, geometrije veza i ortotropne prirode tkane strukture. Poseban naglasak stavljen je na objektivno kvantificiranje hrapavosti profila u različitim smjerovima mjerenja te na interpretaciju dobivenih rezultata u kontekstu strukturne simetrije i dijagonalne geometrije tkanina. Eksperimentalni dio proveden je na uređaju Fabric Touch Tester (FTT), pri čemu je analizirano sedam tkanina različitih vezova (platno, panama, rips, keper i atlas) proizvedenih od iste pamučne pređe kako bi se eliminirao utjecaj sirovinskog sastava. Mjerenja su provedena u smjeru osnove (0°), potke (90°) te u zakrenutim smjerovima (45° i 135°), čime je omogućena analiza ortotropnosti površinske hrapavosti. Dobiveni sirovi profili dodatno su filtrirani i statistički obrađeni, a hrapavost je kvantificirana primjenom parametra srednjeg kvadratnog odstupanja profila Rq. Rezultati pokazuju da, unatoč ortotropnoj prirodi tkanina, površinska hrapavost ne pokazuje strogo ortotropno ponašanje. Najviše vrijednosti parametra Rq uočene su u dijagonalnom smjeru od 45° kod svih analiziranih uzoraka, bez obzira na vrstu veza. Polarni dijagrami dodatno potvrđuju da strukturno simetrični vezovi ne jamče simetričnu raspodjelu hrapavosti profila. Dobiveni rezultati naglašavaju potrebu za višesmjernim mjerenjem hrapavosti tkanina te ukazuju na ograničenja interpretacije površinskih svojstava isključivo u glavnim konstrukcijskim smjerovima.*

***Ključne riječi:*** *tkanina; hrapavost površine; vezovi; ortotropnost*

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## 1. Introduction

The geometry of a woven fabric determines the manner in which surface roughness manifests in the warp and weft directions. Differences in yarn density, yarn type, interlacement pattern, and fiber morphology influence the position of peaks and valleys in the surface relief of the fabric [1].

In surface roughness testing, measurements are most commonly performed in the warp and weft directions, since these directions follow the constructional logic of the woven structure. Measuring roughness in these directions provides the most representative description of the structural logic of the fabric, as the profilometer follows the linear characteristics of the yarns. However, the complexity of the structural interaction between warp and weft becomes more pronounced in rotated directions, most commonly at angles of 45° and 135°. In these directions, the profilometer stylus does not predominantly traverse a single yarn system, but intersects regions of their mutual contacts and interlacement distribution, i.e., their contact points and mutual interactions. This results in a different distribution of microgeometric irregularities that is not necessarily predictable from measurements in the principal directions. Therefore, the overall surface roughness of a woven fabric cannot be fully interpreted solely through the principal axes, and rotated directions provide an additional dimension for understanding surface morphology.

### 1.1. Orthotropic Nature of Woven Fabrics

Orthotropy denotes the property of a material to exhibit different physical and mechanical characteristics in three mutually perpendicular directions. Unlike isotropic materials, whose properties are identical in all directions, orthotropic materials possess three orthogonal axes of symmetry along which their behavior can be described and predicted. In the case of woven fabrics, this means that the material exhibits different surface properties in the warp and weft directions, while in other directions the behavior cannot be reduced to a simple superposition of these two principal directions. Woven fabrics belong to this group because their structure is defined by the warp and weft yarn systems, whereas the thickness direction may be neglected in the analysis of surface properties [1].

Although fabrics produced in plain weave and its derivatives may exhibit a high degree of structural symmetry, a significant proportion of fabrics possess asymmetrical or diagonally structured constructions, such as twill and satin weaves [2]. Such structures introduce a pronounced diagonal geometry that may lead to deviations from ideal orthotropic behavior.

In diagonally structured fabrics, the distribution of surface irregularities depends on the interaction of constructional parameters of both yarn systems. The roughness profile therefore depends not only on the weave type but also on yarn density and the structural configuration of the fabric. Higher yarn density generally results in less pronounced peaks and a more uniform surface, whereas lower density produces more pronounced peaks and greater asymmetry of the surface relief.

### 1.2. Surface Roughness of Woven Fabrics

Surface roughness is defined as the set of microgeometric irregularities on a material surface that are significantly smaller than the dimensions of the observed specimen [3]. In engineering and textile science, roughness is important because it affects optical, tactile, mechanical, and functional properties of materials. In woven fabrics, the microstructure of roughness is formed hierarchically: first at the fiber level, then within the yarn structure, and finally, as a result of warp and weft interlacement, at the woven fabric surface. Therefore, roughness parameters must be interpreted considering textile-specific microgeometric and morphological characteristics.

The roughness profile represents height deviations relative to the mean line of the surface. Any surface must be considered as a combination of form, waviness, and roughness, where roughness refers to high-frequency variations of the profile. Roughness parameters are classified according to profile type and include amplitude, wavelength, hybrid, and curve parameters [3]. For woven fabrics, amplitude parameters are the most suitable because they describe the relationship between peaks and valleys and directly reflect the structural nature of the surface. The prefix R is most commonly used to denote roughness parameters obtained after wavelength filtering [4].

A graphical representation of the primary and filtered roughness profile of a woven fabric, obtained by removing wavelengths smaller than 0.5 mm, is shown in Fig.1. Raw data obtained through contact measurement represent a two-dimensional set of values that does not provide a reliable representation of the actual surface roughness; therefore, mathematical processing is necessary [5].

In the first step, the overall form of the surface is removed, most commonly by applying the least squares method, in order to compensate for possible tilt or nominal curvature of the specimen. Subsequently, filtering is carried out to separate roughness from other profile components: the $\lambda s$ filter removes

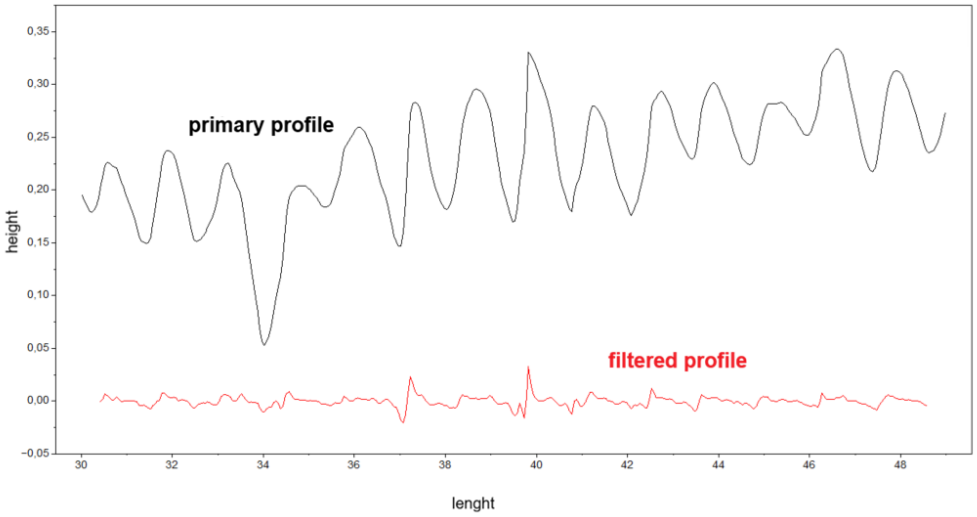



**Fig.1** Representation of the primary and filtered roughness profile of a woven fabric

short-wavelength irregularities, while the λc filter separates roughness from waviness, where longer wavelengths represent waviness and shorter wavelengths represent roughness.

Standards ASME B46.1-2019 and ISO 21920 and ISO 16610-31:2016 recommend the application of the Gaussian filter as the most precise method for separating long- and short-wavelength components of the profile. Only after such processing is performed does the roughness profile accurately correspond to the true microstructure of the woven fabric surface.

### 1.3. Surface Roughness Parameters

There are several parameters used to describe surface roughness. The two most commonly applied to woven fabrics, which best represent amplitude deviations of the profile, are *Ra* (arithmetical mean deviation) and *Rq* (root mean square deviation). The selection of an appropriate parameter depends on the type of material and the objective of the analysis; in textile structures, it is necessary to consider the specific microgeometric and morphological characteristics of the surface.

The *Ra* parameter is most frequently used due to its simplicity of interpretation. It represents the average distance of peaks and valleys from the mean line of the profile. However, one of its limitations is that it does not distinguish between peaks and valleys, since all values are taken in absolute terms. Two surfaces with different microstructures but identical average amplitude values may therefore exhibit the same *Ra* value, which limits its applicability in detailed textile analysis. Consequently, *Ra* does not provide complete information on the distribution of profile heights, particularly for surfaces with pronounced local irregularities.

By representing the arithmetic mean of the absolute ordinate Z($x$) over the evaluated profile length, *Ra* is defined by Equation (1):

$$R_a = \frac{1}{L}\int_1^l |Z(x)dx| \quad (1)$$

The *Rq* parameter, defined as the root mean square deviation of the profile, is more sensitive to larger peaks because the profile height deviations are squared [6]. For this reason, it better reflects real differences between surfaces and is particularly useful in textile surface research, where pronounced surface irregularities may indicate specific structural effects of weaving. Compared to *Ra, Rq* emphasizes extreme profile values more strongly, which in woven fabrics are often associated with yarn position and surface contacts. In addition, *Rq* is significant in the evaluation of optical properties, since surface reflection and gloss can be statistically related to squared profile deviations.

*Rq* is defined as the square root of the mean of the squared profile heights along the entire evaluation length in the x-direction, as given by Equation (2):

$$R_q = \sqrt{\frac{1}{l}\int_0^l Z^2(x)dx} \quad (2)$$

## 2. Experimental Part

The objective of the experimental part of this study was the objective quantification of the surface roughness of woven fabrics using the Fabric Touch Tester (FTT) and the evaluation of the influence of constructional parameters on surface geometry and

the resulting roughness profile values. The research focuses on analyzing surface roughness in different measurement directions to examine woven fabric behavior in relation to its orthotropic structure.

## 2.1. Samples

The study used cotton fabrics produced on the same laboratory weaving machine DW598 (Fanyuan Instrument) in order to eliminate differences in technological weaving parameters (Fig.2). For all samples, the same yarn was used in both warp and weft, thereby completely eliminating potential raw material influence on surface roughness.



**Fig.2** Laboratory weaving machine DW598 by Fanyuan Instrument

A single combed cotton yarn (100% cotton), with a linear density of 36 tex and 505 twists per meter in the S-direction, was used. This ensured that any observed differences in roughness originated exclusively from structural characteristics of the woven fabrics.

The fabrics were woven in seven different weave types (Table 1), with variations in warp and weft densities, in order to cover a broader range of structural configurations and their possible relation to changes in surface properties. The selection of different weaves enabled comparison between fabrics with simple and diagonally emphasized geometries.

**Tab.1** Characteristics of the tested samples

| Sample designation | Weave type | Warp / weft density [threads/cm] |
|---|---|---|
| P1/1 | P1/1 | 24/24 |
| Pa2/2 | Pa2/2 | 22/22 |
| R1/1(2+2) | R1/1(2+2) | 22/20 |
| K1/3S | K1/3S | 18/18 |
| K2/2S | K2/2S | 20/20 |
| A1/4(2)_20 | A1/4(2) | 22/23 |
| A1/4(2)_24 | A1/4(2) | 22/24 |

## 2.2. Testing Methodology

*Determination of Roughness Profiles*

Surface roughness of the woven fabrics was analyzed using the Fabric Touch Tester (FTT), a device for the assessment of fabric comfort/handle, shown in Fig.3, which simultaneously measures compressional, thermal, bending, and surface properties of materials.



**Fig.3** Device for testing fabric comfort (Fabric Touch Tester – FTT)

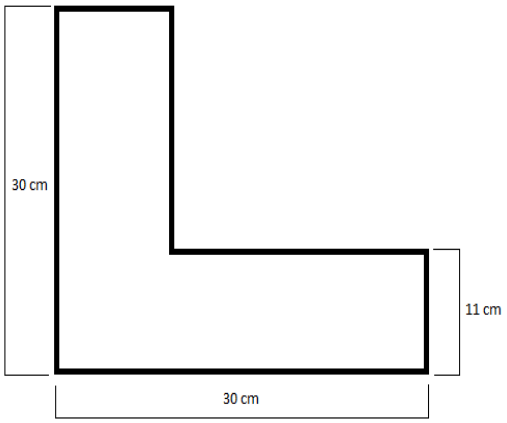



**Fig.4** Dimensions of samples for FTT testing

Prior to testing, the samples were prepared appropriately to ensure accurate FTT analysis. From each woven fabric, specimens of dimensions shown in Fig.4 were prepared in the warp and weft directions, as well as in rotated directions at an angle of 45° relative to the warp direction. Thus, each sample was tested on the FTT in directions parallel to the warp at angles of 0°, 90°, 45°, and 135°. In this way, comparison of roughness profiles in different measurement directions for the same woven fabric sample was enabled.

*Data Preparation and Statistical Processing*

Data preparation and processing were based on .xls files generated by the FTT device, with only roughness data used for analysis. Results were categorized according to measurement direction (horizontal and vertical), and in addition to warp and weft directions, samples were evaluated in rotated directions (45° and 135°). This enabled verification of the hypothesis regarding different roughness distribution as a consequence of the orthotropic nature of woven fabrics. Since the FTT device does not measure roughness from the very beginning of probe displacement, data in the range from 0 to 30 mm and above 49 mm were excluded, as contact was not active in these regions. Thus, profile segments not representing the actual woven fabric surface were removed from analysis.

The remaining data were classified into intervals with a step of 0.05 mm to homogenize the profiles and ensure uniform statistical processing. Classification was performed consistently for all samples and directions to ensure comparability of results. For each sample, repeated measurements were compiled and the arithmetic mean was calculated for each measurement direction. The resulting datasets were imported into OriginPro software to generate primary roughness profiles for each direction (0°, 90°, 45°, and 135°). Based on these processed profiles, the Rq parameter was calculated for each direction and used for further analysis and interpretation.

## 3. Results and Discussion

Polar diagrams (Fig.5) reveal deviations from the expected symmetry of the roughness parameter, with the most pronounced increase observed in the 45° direction, suggesting deviation from typical orthotropic behavior. In a two-axis observation system, woven fabrics are generally considered structures with two principal axes of symmetry: warp (0°) and weft (90°). In these directions, extreme values of key mechanical properties, such as tensile and elongation properties, are typically found. However, when analyzing surface roughness, i.e., the root mean square deviation (*Rq*), a significant deviation from this expected behavior is observed. This indicates that surface roughness does not behave as a classical orthotropic property but rather exhibits pronounced directional dependence. Polar diagrams visually demonstrate this dependence and clearly indicate asymmetric roughness distribution within the woven fabric plane.

All analyzed samples show the highest *Rq* values at 45°, while minimum values are generally observed in the weft direction (90°). This trend cannot be attributed solely to weave symmetry, as diagonally oriented maxima also occur in woven fabrics with symmetrical constructions. These results confirm that structural symmetry of the weave does not necessarily imply symmetrical distribution of surface roughness properties. The most plausible explanation lies in yarn twist, which is oriented in the same direction in all samples. Due to this twist, the woven fabric surface develops a more pronounced microrelief structure in the diagonal direction, leading to increased roughness at 45° relative to the principal axes. This further confirms that total woven fabric roughness cannot be fully interpreted solely through warp and weft directions, as rotated directions provide an additional dimension for understanding surface morphology.

For a more comprehensive understanding of the influence of woven fabric construction and yarn twist on the polar distribution of roughness, future research should include measurements with finer angular resolution. This would allow more detailed interpretation of deviations and more precise identification of structural influences on surface properties.

## 4. Conclusion

Although woven fabrics may be considered planar structures with two principal axes of symmetry (warp and weft), the results of this study demonstrate that surface roughness does not strictly follow this orthotropic logic. The highest Rq values were observed in the diagonal direction (45°) for all analyzed samples, regardless of weave type and structural symmetry. This confirms that structural symmetry of the weave does not necessarily imply symmetrical distribution of surface properties.

The results indicate that analysis limited exclusively to warp and weft directions does not provide a complete understanding of surface roughness distribution. Dominant roughness variations are not confined to principal construction directions but vary depending on measurement orientation. Polar diagrams clearly show asymmetric Rq distribution within the woven fabric plane, emphasizing the directional dependence of this property.

The influence of yarn twist is particularly significant, as its consistent orientation contributes to a more pronounced microrelief structure in diagonal directions. Thus, roughness distribution cannot be unambiguously linked solely to weave type but must be understood as the result of interaction between structural parameters and yarn geometry.

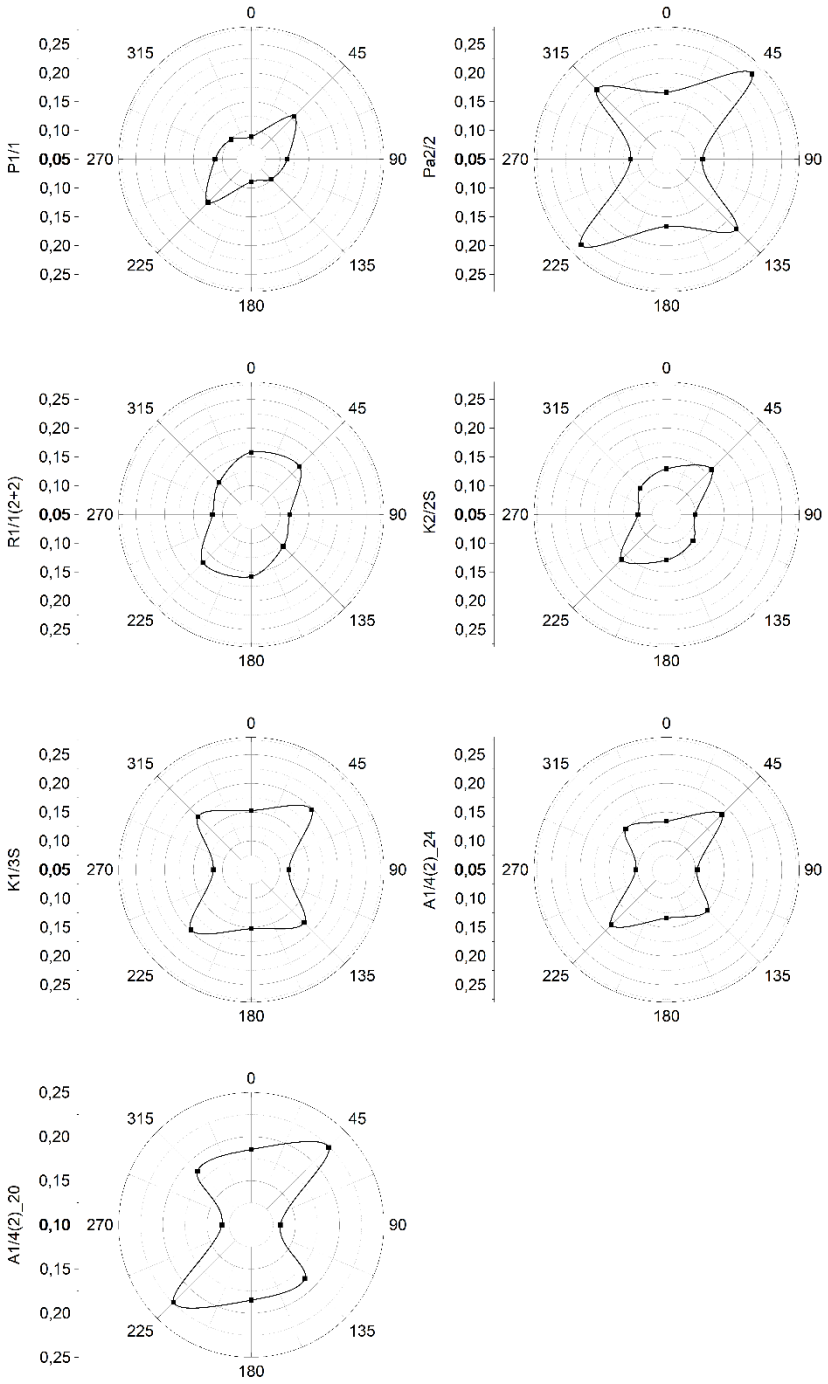



**Fig.5** *Rq* roughness parameter in the principal and rotated axes of symmetry

The findings highlight the importance of a multidirectional approach to surface roughness measurement, enabling more realistic interpretation of surface properties and improved correlation between structural characteristics and measured roughness values. Future research should incorporate finer angular divisions to allow more detailed analysis of directional distribution and deeper understanding of the relationship between woven fabric structure and objectively measured surface characteristics.

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**Statement on the Use of AI Tools:** An AI tool was used for structuring the original text and proofreading

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