TRANSFORMATION OF METROLOGY PROCEDURES FOR SURFACE QUALITY EVALUATION USING PROFILE PARAMETERS

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Surface roughness measurement is key for understanding fundamental interactions at the microscopic level and designing and optimising the surface in a wide range of applications, including tribology, adhesion, and overall performance of components in specific environments. ISO standards specify the methodology for the surface roughness measurements. However, these measurement methodologies are updated from time to time to match the technological advancement in measuring tools, making them much more accurate and real. Recently, the methodology for measuring profile surface roughness parameters was updated by ISO to make it much better aligned with areal surface roughness parameters. Therefore, this paper discusses changes in measuring methodology for determining the profile roughness parameters according to the new and old ISO standards, along with a quantitative comparison of the profile roughness values obtained using new and old ISO standards. A surface created by an abrasive water jet was used as an exemplary surface for quantitatively comparing profile surface roughness parameters using old and new ISO standards.

KEYWORDS

profile roughness parameters, surface characterization, machining quality of surface, abrasive waterjet

1 INTRODUCTION

Evaluation of material surface topography was previously used mainly in the engineering industry. Today's era brings new design trends and demands on the functional properties of the surface, emphasizing the resulting quality, the overall economic demand and, at the same time, a low ecological burden on the environment. All of this affects the current development of production technologies and equipment. New manufacturing processes and measurement methods are coming into practice, which provide us with new, improved surface properties and more extensive information about the newly created surface. At present, this domain is also gaining attention in the electronic and optoelectronic industries due to its ability to analyze surface topography at the nanometer scale and in biomedical applications. However, evaluating these new improved surface properties also means updating the methodology used for evaluating the surfaces generated.

In 2021, new standards of the ISO 21920 series "Geometric product specifications (GPS) - Surface structure: Profile" were adopted, consisting of three separate parts. Part 1 deals with the topic "Surface Structure Indication", which defines the rules for specifying the properties of a profiled surface. Part 2 focuses on "Terms, definitions and parameters of surface structure" and develops terminology as well as concepts and parameters for determining surface properties by touch. Section 3 deals in detail with "Operator Specification" by defining a complete specification operator for surface properties using profile methods.

The new ISO 21920 series of standards was developed in response to technological advances in manufacturing processes and the need for more accurate and unambiguous surface roughness evaluation. Implementing these standards ensures greater accuracy, consistency and efficiency in surface texture evaluation. Older standards contained inconsistent definitions and different methodologies for calculating parameters. ISO 21920 unifies and clarifies all key aspects. The older standards were developed when analogue measurements were used and primarily focused on subtractive manufacturing (e.g. turning, milling). The new standard reflects developments in digital measurement and production automation and is adapted to new manufacturing methods, such as additive manufacturing, where surfaces are often more complex. Therefore, this transformation from old standards to new standards is necessary to be at par with the technological demands of the industry in order to have a better and correct estimation of the surfaces.

Earlier standards can still be used, even if they are not official international standards and are considered obsolete. The transition to the new standards will take several years in practice. It brings changes, such as new graphic symbols or tolerance acceptance rule (ISO 21920-1), definitions of new terms and parameters (ISO 21920-2), one procedure for all types of profiles (ISO 21920-3) and more [ISO 21920-1:2021, ISO 21920-2:2021, ISO 21920-3:2021].

The application of the new standards in practice will be slow, as specifications on technical drawings made before the new standards are still valid and binding according to earlier standards. The evaluation of the roughness profile parameters defined by the ISO 4287 standard takes place according to the decision rules described in ISO 4288 [ISO 4287:1998, ISO 4288:1998]. The specifications made on new drawings according to the new ISO 21920-1 standard determine that the parameters are defined in ISO 21920-2 and the decision rules are described in ISO 21920-3 [ISO 21920-1:2021, ISO 21920-3:2021]. Most of the ISO 4287 profile parameters are included in ISO 21920-2 [ISO 21920-2:2021, ISO 4287:1998].

The definition of some parameters is slightly different in the new standard so that it can lead to different results. Likewise, changing the evaluation workflow leads to different results. In both practice and science, one must prepare for possible differences in profile parameter values. For industry, this means updating tolerance limits on technical drawings. For science, this means knowing the measurement and evaluation procedure in order to ensure the comparison of results.

In addition to differences in already existing parameters, the standards of the ISO 21920 series introduce new parameters that effectively correspond to the characteristics of modern technical surfaces. The same concepts are applied here as in the 25178-2 standard for areal surface structure [ISO 25178-2:2021]. Areal surface parameters are used to quantify surface structure in many publications [Stolárik 2024]. However, areal surface parameters cannot always be used because they have their limits, which is where profile parameters can be used.

In previous studies [Hloch 2012, Valíček 2007], profile roughness parameters were evaluated using a procedure mentioned in the old ISO standard, leading to imprecise values compared to areal parameters. This discrepancy primarily arose due to differences in the evaluation procedures outlined in the older ISO standard. Therefore, this study aims to compare the profile roughness evaluation procedure of the old ISO 4287 and new ISO 21920 standards to highlight their impact on measurement accuracy and reliability. The quantification of the profile roughness parameters was determined on the surface generated by an abrasive water jet under optimal conditions, generating the best cutting quality. Even though the paper is focused on AWJ-generated surfaces, the measurement procedure is also valid for any machined surfaces generated by different machining processes.

2 MATERIALS AND METHODS

2.1 Experimental setup

The experimental material was Titanium Grade 2. The surface used to evaluate the profile surface roughness was generated on an abrasive water jet technological device with a 2D X-Y cutting table PTV WJ2020-2Z-1xPJ. Australian garnet abrasive grain with MESH 80 was used, and the abrasive mass flow was 400 g.min-1. The water pressure was produced using pump PTV 75-60. The working pressure was 400 MPa. The stand-off distance between the focusing tube and the experimental material was 4 mm. The diameter of the water nozzle orifice was 0.33 mm, the focusing tube diameter was 1.02 mm, and the traverse rate was 50 mm.min-1.

A Mitutoyo SV-C3200 W4 device was used to analyze the topography of the surface created by abrasive water jet technology in detail. The measured data were analyzed using the software MountainsSPIP, according to the cancelled standard ISO 4287 and the new standard ISO 21920-2 [ISO 21920-2:2021, ISO 4287:1998].

2.2 Standard roughness parameters

Surface profile parameters provide us with a quantified form of description of surface topography properties. Roughness is a measure of the unevenness of the surface of a body, which arises as a result of technological processing or a natural consequence. Roughness is divided into macrostructure and microstructure. The geometric macrostructure includes surface deviations in shape and position. The geometric microstructure includes waviness and roughness, which are evaluated using profile parameters. The parameters of the surface profile include the *P*-parameter (parameter calculated from the basic profile), the R-parameter (parameter calculated from the roughness profile) and the W-parameter (parameter calculated from the waviness profile). The separation of the components of the surface structure is achieved by filtering them. When quantifying the topography of the surface using standardized parameters, it is important to choose the filter settings of the desired profile correctly. The methodology for assessing the surface structure is defined by the ISO 4288 standard when evaluating parameters according to ISO 4287 [ISO 4287:1998, ISO 4288:1998]. When evaluating profile parameters according to ISO 21920-2, the cut-off setting is defined in standard 21920-3 [ISO 21920-3:2021, ISO 21920-2:2021]. When evaluating the sample surface, where the average arithmetic deviation of the profile is in the range of 2 µm > *Ra* < 10 µm, filter (cut-off) λc = 2.5 mm is used, according to the new L-filter = 2.5 mm. In engineering practice, the R-parameters of the roughness profile are used in the assessment of surface quality, whose representatives are defined here in more detail according to ISO 4287 and ISO 21920-2 [ISO 21920-2:2021, ISO 4287:1998], see Table 1.

To determine the quality of the surface, it is necessary to use several standardized R-parameters. When using one parameter, only a partial view of the surface quality is available, which can lead to wrong conclusions about the overall quality of the workpiece. The Ra parameter, commonly used to assess roughness, provides limited insight into surface characteristics. In contrast, the Rq parameter is more responsive to variations in the profile's unevenness, though it still represents a mean deviation. Another key parameter, Rz, measures the maximum peak height of the profile, giving us information about the overall height variation within the surface. The information about higher protrusions or depressions in the measured surface is informed by the parameters *Rp*, the largest profile protrusion height, and *Rv*, the largest depth of the profile depression. Individual parameters have only a limited ability to tell about the structure of the analyzed surface. Evaluating the surface using multiple roughness parameters offers a more detailed understanding of its characteristics.

	ISO 21920-2	ISO 4287
Ra	**Arithmetic mean height** The arithmetic mean height parameter is the arithmetic mean of the absolute values of the ordinate values	**Arithmetical mean deviation of the assessed profile** The arithmetical mean deviation of the assessed profile is the arithmetic average of the absolute values of the ordinates *Z(x)* in the range of the basic length *lr.*
Rq	**Root mean square height** The root mean square height parameter is the square root of the mean square of the ordinate values.	**Root mean square deviation of the assessed profile** The root mean square deviation of the assessed profile is the square mean of the ordinates *Z(x)* in the range of the base length *lr.*
Rp	**Mean peak height** The mean peak height parameter is the mean value, from all section lengths, of the largest peak height of each section length.	**Maximum profile peak height** The maximum profile peak height parameter is the height *Zp* of the highest projection of the profile in the range of the basic length.
Rv	**Mean pit dept** The mean pit depth parameter is the mean value, from all section lengths, of the largest pit depth of each section length	**Maximum profile valley depth** The maximum profile valley depth parameter is the depth *Zv* of the lowest profile depression in the range of the basic length *lr*.
Rz	**Maximum height** The maximum height parameter is the mean value, from all section lengths, of the per section sum of the largest peak height and largest pit depth.	**Maximum height of profile** The maximum height of the profile parameter is defined as the sum of the height Zp of the highest projection of the profile and the depth Zv of the lowest depression of the profile in the range of the basic length *lr*.

Table 1. Roughness profile parameters [ISO 4287:1998, ISO 21920-2:2021].

2.3 Measurement methodology

From the generated surface, the cut area was measured in 20 lines (Fig. 1.) at a distance of 0.5 mm from the edge of the water jet entering the material and 0.5 mm from the edge of the water jet exiting the material using a Mitutoyo SV-C3200 W4.

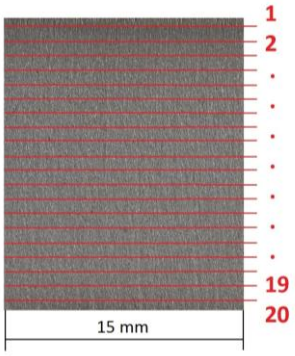

Figure 1. Scheme of the location of measured lines.

Roughness profiles were obtained from the measured lines with a length of 15 mm after filtering out the unevenness and waviness of the surface. Subsequently, according to ISO 4287 and ISO 21920-2 standards, cut-off 2.5 mm, the roughness height parameters were calculated [ISO 21920-2:2021, ISO 4287:1998]. The selected profile height roughness parameters *Ra*, *Rq, Rp, Rv* and *Rz* are shown in Table 1. The roughness profile parameters obtained quantify the cutting wall surface structure of the sample generated by AWJ.

2.4 Differences in workflow

One of the main changes in evaluating the surface profile, see Fig.2 between the old and new ISO standards is the measurement methodology. According to the old ISO 4287, the primary profile was obtained after removing the nominal shape, followed by applying a λs filter [ISO 4287:1998]. In ISO 21920-2 these operations are reversed to conform to standard practice for surfaces, which is used to analyse areal surface roughness parameters [ISO 21920-2:2021]. Furthermore, the label for the filters λs, λc, λf has changed to S-filter, L-filter, and F-operation, respectively.

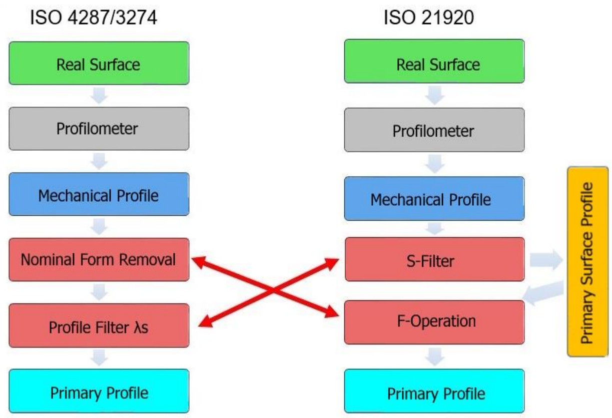

Figure 2. Schematic representation of the change in workflow when evaluating a primary profile.

3 RESULTS AND DISCUSSION

The topography of the surface created by AWJ technology changes with the increased depth of the cut. As the depth of the cutting groove increases, the jet's kinetic energy decreases, and thus, surface irregularities increase, i.e., their height amplitudes increase, and their spatial frequencies decrease at the same time. This is because the mechanism of material removal changes from a predominant tensile and shear stress to a compressive stress [Valíček 2009].

Table 2 presents the values for different profile roughness parameters. Initially, the cutting process experiences high deformation stress. However, as the abrasive jet exceeds the material's elastic limit and penetrates deeper, energy loss occurs, leading to a decrease in surface quality near the top side of the kerf. Similar observations were also observed in the previous study using a titanium workpiece and its interaction with AWJ [Hloch 2011]. In the subsequent portion of the cut, the hydromechanical conditions of the cutting section stabilize. The experimental conditions were selected to achieve optimal surface quality. As a result, the induced energy of the jet remains consistent for the further process, which is also reflected in the roughness parameters measured from the individual lines across the generated kerf depth.

The rules and procedures for assessing the surface structure are specified by the ISO 4288 standard, which defines the basic length *lr* and the necessary evaluated length *ln* (Fig. 3) for measuring the *R*-parameters of periodic and non-periodic surfaces [ISO 4288:1998]. The surface profile (Fig. 3) is divided into five sampling lengths over which five estimated parameter values are calculated and averaged. The ISO 4287 [ISO 4287:1998] standard describes the parameters and their calculation. The new ISO standard defines the profile parameters on the evaluated length with the designation le. This means that the parameter values are no longer calculated several times from the base length and then averaged, as was the case before with old ISO standards. Only one Ra value (and other profile parameters) is calculated on the evaluated profile (Fig. 3). The only exceptions of this updated methodology are the roughness profile parameters *Rp*, *Rv* and *Rz*, which are still averaged to reduce the influence of outliers. These parameters react sensitively to local height fluctuations on the examined roughness profile.

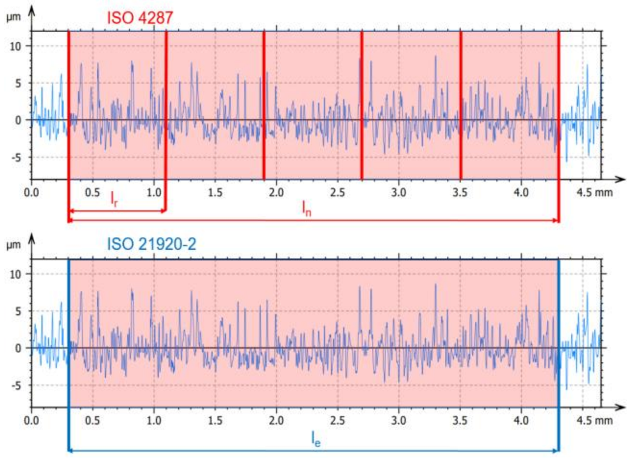

Figure 3. The difference in defining parameters from the basic length and the evaluated length.

	ISO 21920					ISO 4287				
	***Ra* [µm]**	***Rq* [µm]**	***Rz* [µm]**	***Rp* [µm]**	***Rv* [µm]**	***Ra* [µm]**	***Rq* [µm]**	***Rz* [µm]**	***Rp* [µm]**	***Rv* [µm]**
1	4.917	6.170	33.248	16.326	16.922	4.931	6.201	33.396	16.320	17.075
2	3.295	4.107	24.171	10.569	13.601	3.287	4.108	24.043	10.564	13.479
3	3.416	4.369	27.605	10.427	17.178	3.425	4.417	27.701	10.390	17.311
4	3.700	4.619	29.825	13.890	15.935	3.710	4.648	29.629	13.931	15.698
5	3.710	4.613	26.099	12.627	13.473	3.725	4.639	26.225	12.664	13.562
6	3.622	4.585	28.829	12.558	16.271	3.611	4.637	28.635	12.546	16.089
7	4.069	5.020	28.537	12.325	16.213	4.078	5.027	28.302	12.306	15.997
8	3.693	4.622	26.799	13.389	13.410	3.688	4.633	26.706	13.420	13.286
9	3.805	4.762	29.740	14.397	15.343	3.804	4.768	29.666	14.442	15.224
10	3.744	4.628	27.591	13.909	13.682	3.726	4.659	27.511	13.950	13.561
11	3.857	4.881	30.178	13.044	17.135	3.835	4.871	29.569	12.484	17.084
12	3.984	5.104	35.053	15.145	19.908	3.971	5.135	34.732	15.178	19.554
13	4.142	5.115	28.455	13.492	14.963	4.122	5.151	28.360	13.530	14.830
14	4.489	5.548	28.159	13.692	14.467	4.459	5.547	28.105	13.744	14.361
15	4.333	5.476	33.949	18.368	15.581	4.317	5.488	33.862	18.391	15.471
16	4.858	6.038	34.861	18.465	16.396	4.826	6.031	34.753	18.493	16.260
17	5.445	6.715	35.466	17.311	18.155	5.443	6.827	35.381	17.352	18.029
18	5.589	7.026	37.805	19.975	17.830	5.603	7.096	37.269	19.524	17.745
19	6.659	7.920	38.939	19.712	19.227	6.657	7.971	38.656	19.529	19.127
20	6.791	8.235	40.390	21.444	18.946	6.777	8.328	40.326	21.496	18.830

Table 2. Selected surface roughness profile parameters.

When calculating the profile roughness parameters according to the old and new standards using the same profiles, the values of the observed roughness parameters differ (Table 2). The differences in the values of the parameters *Ra* and *Rq* are due to the change in the evaluated length. According to ISO 4287, the values were calculated five times from the base length and the result was averaged. According to ISO 21920, the values are determined from the entire evaluated length. This difference is shown in Figure 3. However, the profile height parameters *Rz*, *Rp* and *Rv* in ISO 4287 and ISO 21920 are still calculated five times from the base length and then averaged. Therefore, the minimal changes in the values of these parameters were due to the difference in the filtering procedure used to obtain the roughness profile as specified by the new ISO 4287. For implementation in practice, it will be necessary to evaluate the effect of these changes on the products and possibly update the tolerance limits in the technical drawings. The new standard is better adapted to current product specifications despite possible parameter deviations. Although their implementation will be several years away, designers and metrologists are responsible for updating their knowledge and understanding of the new standard.

Although the new standard brings higher accuracy and repeatability, its implementation requires adapting measurement methods, filter settings and tolerances in engineering drawings. The practical significance of this study lies in evaluating the changes in the values of the key roughness parameters (*Ra, Rq, Rz, Rp, Rv*) when using the old and the new standard on the same profiles. It is shown that changing the length of the evaluated section and different filtration procedures can lead to slight variations in the measured values, which is important for industrial applications where the accuracy of surface properties affects the quality and functionality of components. The theoretical contribution lies in deepening the understanding of the impact of new decision rules and metrology procedures on surface topography evaluation. The results show that the modernization of standards leads to greater measurement objectivity but, at the same time, raises questions regarding the compatibility of old and new methods for roughness evaluation.

The discussion of the changes brought by the new ISO 21920 series standards and their implementation in practice opens up space for further innovation and optimization in evaluating surface structure. Manufacturing companies implementing these standards can improve the accuracy and efficiency of surface quality control, but they must also adapt their measuring devices and procedures to the new requirements.

The benefit of modernizing standards is increased accuracy and repeatability of measurements. The previously used approach, where values were averaged from several basic lengths *lr*, could lead to slight measurement variability depending on local surface deviations. The new approach, which determines profile parameters on a single evaluated length le, ensures that the resulting values more closely correspond to the actual profile and take into account its overall structure. However, this procedure can be sensitive to local changes for some parameters such as *Rz*, *Rp* and *Rv*, which is why these parameters are still averaged from the basic length.

With the increasing possibilities of modern measurement technology, the importance of multi-parameter analyses, which can include more advanced parameters and measurements, is also increasing. It provides room for technological development and increases the accuracy of quality assessment.

These results showed differences between the old and new standards. Based on this, in future research, it would be good to verify the effect of using the old and new standards on the measured profiles' results by direct topographic measurements using two different measuring devices.

4 CONCLUSIONS

The present study highlights the differences in surface quality measurements using the old ISO standards and the new ISO standards. It has been shown that the new standards have different sensitivity to the measured surface due to the change in the measurement process. Some of the major conclusions are listed below:

1. The major difference is the way Ra and Rz parameters are defined in the new standard compared to the old standards, which have already been officially replaced internationally. The main differences can be found in the different evaluation lengths of the measured area. The old standards consider the average of five measurements from individual evaluation lengths, while the new standard considers the entire evaluated area.

2. The change in the measurement methodology for Ra and Rz profile parameters according to the new standards gives different measurement results compared to the old standards for the same investigated surface.

3. Setting up the correct filtration for the surface structure is an important part of qualifying the surface topography, which is relevant to the surface data of the measured surface.

4. Several relevant indicators of the R-parameter standards are new for surface quality research in the new standards. In case of an incorrect selection of parameters or filters, it can show a distorted or incorrect view of the surface quality.

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