"Dominant Waviness" - a practice oriented procedure for waviness evaluation

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Abstract

Periodic surface structures (waviness) play a functional decisive part in many areas of surface metrology. For example, waviness at static sealing surfaces such as the cylinder head in combination with the cylinder head gasket can cause leakage. Waviness at rolling and sliding faces increases wear and causes noise. A meaningful waviness analysis using common profile filter techniques according to ISO 4287 and ISO 11562 is almost impossible because the joint interpretation of waviness and roughness with the same cut - off wavelength is often unsuitable. This joint interpretation of the waviness and the roughness is being avoided by the concept of "dominant waviness" (Dominante Welligkeit) as introduced in the following article. The procedure isolates periodic form deviations independent of the wave range of roughness. The WD-Profile, concerning its horizontal as well as its vertical characteristics determined by the WD - parameters, serves as a basis for the analysis.

1. Waviness as a critical form deviation

1.1 Limits of waviness analysis according to DIN EN ISO

Technical surfaces are usually characterized with contact stylus instruments. Due to the experience, that short- and long wave signal components in a profile of a technical surface have different causes and different functional influence, they have been evaluated separately in the roughness- (R-Profile) and waviness profile (W-Profile). For the separation of long- and short wave profile components, profile filter with a cut off wavelength according to DIN EN ISO 4288 in a grid of 0,08 / 0,25 / 0,8 / 2,5 / 8,0 mm are employed. The selection criteria depend upon the geometrical character of the present roughness. There is a distinction to be made between non periodic roughness (e.g. ground surfaces) and periodic roughness (e.g. turned surfaces). The cut off wavelength for non periodic roughness profiles has to be selected according to the expected Rz- respectively Ra- value and that one of periodic roughness profiles according to the estimated RSm parameter. Whether the present profile is non periodic or periodic is left to the decision of the operator.

The term waviness is understood as a nearly periodic form deviation which can occur in the short wave range as well as in the long wave range of the surface profile. The filtering leads with the given wavelength grid almost always to a distorted waviness profile. Figure 1 shows a surface profile with waviness. In this case evaluation according to DIN EN ISO 4288 requires a cut off wavelength of 0.8mm. The result of the evaluation is the W-Profile marked as a black line which displays a distinct smaller amplitude in contrast to the present waviness component. The profile example shows, that selective evaluation of periodic signal components according to DIN EN ISO 4288 is limited. Reason for that are the selection criteria and the given grid of the wavelengths on the one hand, and on the other hand the fact, that the given filter transfer characteristic as a low pass is unsuitable for the evaluation of periodic signal components.

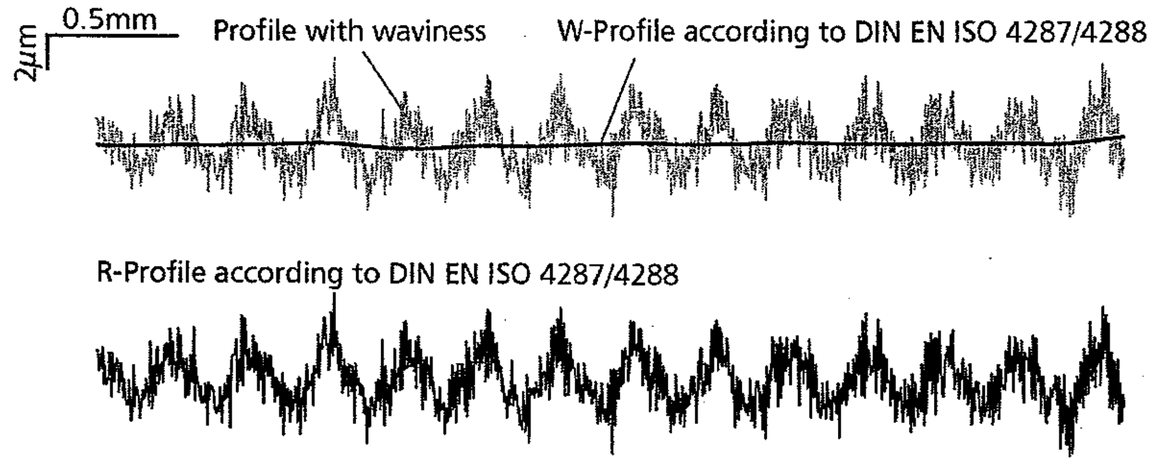

Figure 1: Evaluation of waviness and roughness according to DIN EN ISO 4287/4288.

The result of a low pass filtering process is a mixture of wavelengths greater than the cut off wavelength. The periodic form deviation usually located in this mixture of wavelengths is consequently almost always transferred uncompletely with its amplitude, superimposed for the most part with long wave- , and depending on the cut off wavelength with short wave signal components too.
The following evaluation method „dominant waviness" is in comparison with that a reliable manner in order to characterize periodic profile components in a functional sense.

1.2 Some functional relevant profile characteristics and their evaluation

Figure 2 shows the unfiltered profile of a milled joint face which has - for example with a flat packing - the function of tightness.

Figure 2: Profile of a milled surface.

Schematically looked upon, short wave non - periodic, periodic and long wave non – periodic components can be distinguished. Viewed as ideal these three components are represented in figure 3.

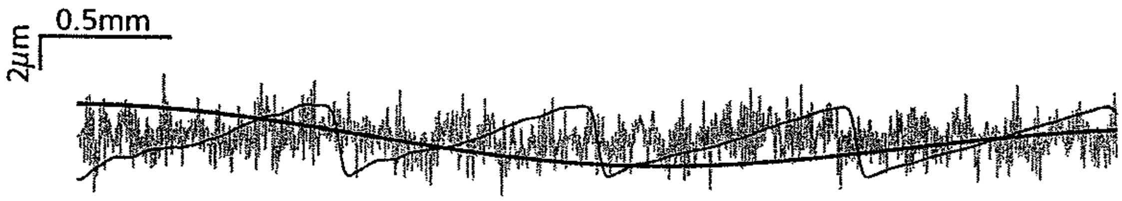

Figure 3: Separating the milled surface in short wave random, periodic and long wave random components.

The short wave non - periodic components influence the grouting with the flat packing. Thus they also influence the distortion characteristics and the material compaction behaviour after tightened the bolts. They can e.g. be estimated by Rz. In risk of leakiness by horizontal close side by side profile height differences Rmax can additionally be tolerated.
Especially the valleys of the periodic components of milled surfaces, which show high interconnectivity, have to be filled up by the seal. They have the greatest effect on the function of tightness. The horizontal and vertical characteristics of the periodic structure over the parameters of the "dominant waviness" are evaluated.
The long wave non – periodic components must be of such a kind that the sealing can easily follow their course. Properties such as strong curves or steps have to be avoided and can be evaluated over WT. The functional behaviour of a surface depends on the interconnection of roughness, periodic and non - periodic waviness. The more finer the roughness components the stronger the influence of the waviness on the functional behaviour. There are several examples to use the concept of "dominant waviness", e.g. the characterization of wear or noise.

2. The definition of „dominant waviness"

The evaluation of surfaces according to "dominant waviness" extracts periodic structures of the surface that comply with certain dominance criteria. The procedure is described in the guideline VDA 2007. From figure 4 it becomes clear that "dominant waviness" is just a subset of periodic form deviation. The periodic form deviation again is a subset of waviness according to DIN EN ISO.

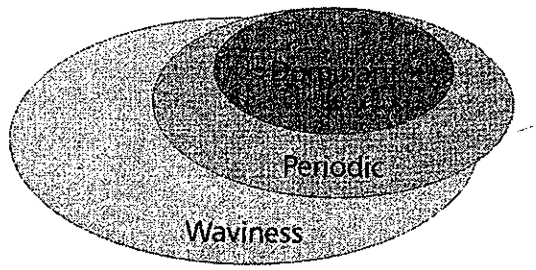

Figure 4: Waviness, periodic form deviation, dominant periodic departures.

The result of the evaluation according to "dominant waviness" is a totally new kind of profile the WD-profile. The so-called WD - parameters are derived from the WD-Profile. The WD-Profile does not replace the W-Profile and the parameters derived from the W-Profile.

3. The algorithm for determination "dominant waviness"

The term "dominant waviness" is understood as quasi periodic form deviations which can occur in the range of long wave form deviations as well as in the range of short wave roughness. By definition the analysis of the "dominant waviness" takes place in a given wavelength band in the range $0{,}02\ mm < \lambda < ln/5$, with ln the evaluation length. This definition was determined empirically and has proved to be very practical. In figure 5, the schematic example of an ideal sinusoidal profile z(x) represents the wavelength range.

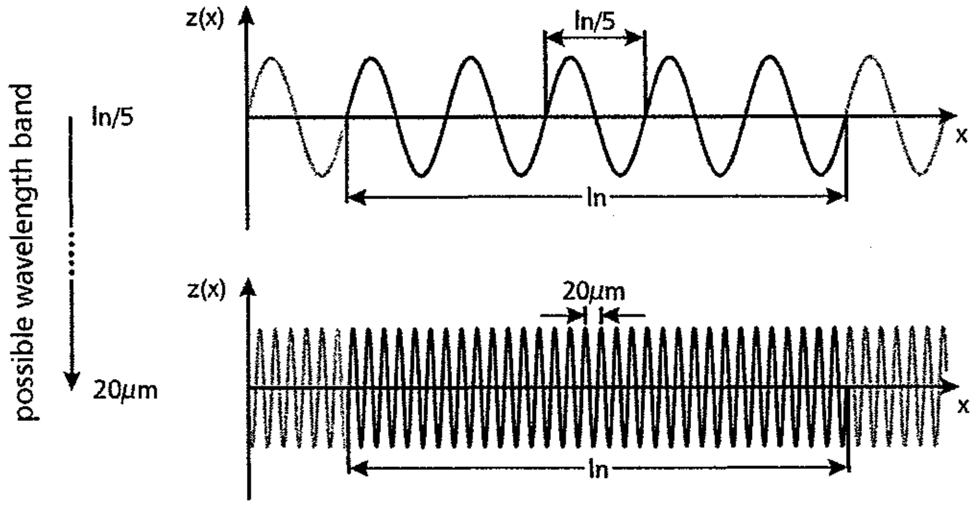

Figure 5: Wavelength range for analysis of "dominant waviness" represented by an ideal sinusoidal profile z(x).

The evaluation length ln has to be chosen either according to DIN EN ISO 4288 or by means of determined drawing specifications. Purpose of the procedure is the detection of wavelengths with significant periodic form deviation in a given section, the calculation of an average waviness profile from the detected wavelengths and their characterization by parameters. Thereby the evaluation algorithm distinguishes three states: The profile contains no, one or two "dominant" wavelengths.

3.1 Detection of the wavelengths of "dominant" periodic form deviations

The detection of the wavelengths of "dominant" periodic form deviations takes place in the discrete amplitude spectrum of the discrete profile z[n]:

$$A[\Omega]=\left|\sum_{n=0}^{N-1} z[n]\cdot w[n]\cdot \exp(-i\cdot\Omega\cdot n)\right| \quad with \quad \Omega=\frac{2\pi\cdot\Delta x}{\lambda}. \qquad [1]$$

Δx is the digitizing step of the measurement and N the number of the measuring points. w[n] is the so called window function, causing the smoothing of the amplitude spectrum. A periodic form deviation with a wavelength λ_1 leads in the amplitude spectrum to a peak at the spatial frequency $\Omega_1 = 2\pi\,\Delta x/\lambda_1$. The amplitude of the peak thereby depends essentially upon the vertical characteristics, that is the amplitude of the periodic form deviation. Employing a threshold value operator consisting of a horizontal- and vertical threshold therefore leads to the decision, whether a peak in the amplitude spectrum is significant and functionally relevant. If it fulfils the limit criteria at a spatial frequency Ω_1 a peak is dominant and represents a periodic component with dominant wavelength WD1Sm $= \lambda_1 = 2\pi\,\Delta x/\Omega_1$.

3.2 Determination of the WD-Profile for description of "dominant waviness"

In the next step a measure for the vertical character of the detected periodic form deviation needs to be found. For this the so called WD-Profile is being determined, which will be generated by means of a narrow-band bandpass, the so called zero-bandpass. The "Gaussian Filter" according to ISO 11562, well known in form metrology and widespread in use, serves as the basis of the zero-bandpass. The zero-bandpass consists of the combination of a wave filter and a roughness filter, both having a cut off wavelength λc = WDSm. An ideal sinusoidal profile with a wavelength WDSm is so being damped down to 25% of its amplitude by the zero-bandpass. In order for the observed idealized profile to pass the zero-bandpass undamped, the filtered profile needs to be multiplied by 4. According to ISO 11562 the following weighting function for the zero-bandpass can be found:

$$s(x)\cdot\lambda c=\frac{4}{\sqrt{2\pi}\cdot\alpha}\cdot\left(\exp\left(-\frac{1}{2}\cdot\frac{x^2}{(\alpha\cdot\lambda c)^2}\right)-\frac{1}{\sqrt{2}}\cdot\exp\left(-\frac{1}{2}\cdot\frac{x^2}{\left(\sqrt{2}\cdot\alpha\cdot\lambda c\right)^2}\right)\right) \qquad [2]$$

with

$$\alpha=\frac{1}{\pi}\cdot\sqrt{\frac{\ln(2)}{2}}.$$

And the transfer function of the zero-bandpass results in:

$$S(\lambda)=4\cdot\left(\exp\left(-\ln(2)\cdot\frac{\lambda c^2}{\lambda^2}\right)-\exp\left(-2\cdot\ln(2)\cdot\frac{\lambda c^2}{\lambda^2}\right)\right). \qquad [3]$$

In figure 6 the weighting function and the transfer function of the zero-bandpass are plotted. As one can clearly see, the amplitude of a sine wave with wavelength λ = λc = WDSm is transferred with 100%. A sine wave with a wavelength λ > WDSm or λ < WDSm is increasingly damped.

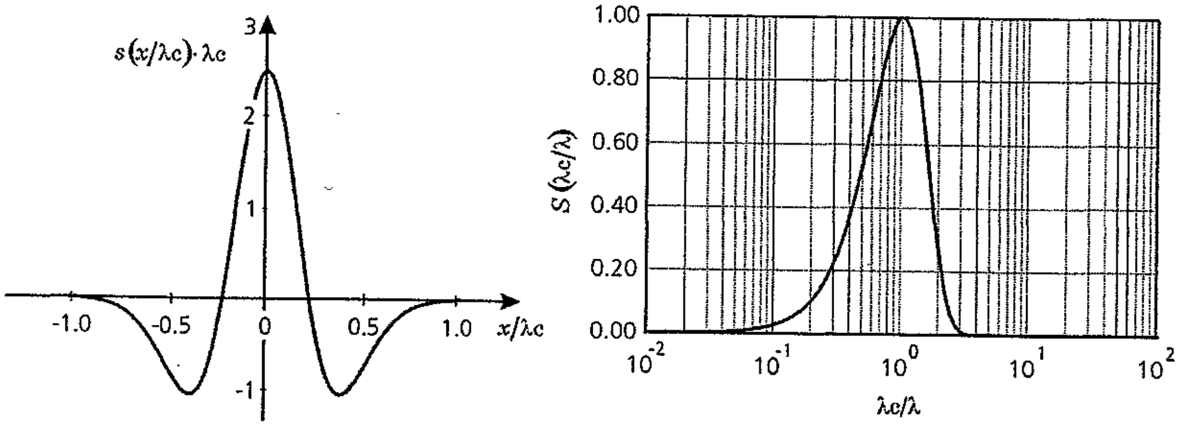

Figure 6: Left: Weighting function of zero-bandpass. Right: Transfer function of the zero-bandpass.

3.3 Parameters of The WD-Profile

The wavelength WDSm as detected in the amplitude spectrum is the first parameter of the WD-Pofile.

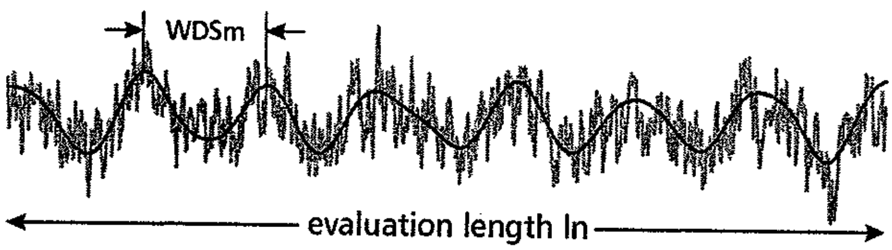

Figure 7: Parameter WDSm: The mean width of the profile elements (wavelength) as derived from the amplitude spectrum.

Following DIN EN ISO 4287, WDSm indicates the mean width of the profile elements. (Figure 7).

The second parameter of the WD-Profile is WDc. It indicates the mean height of the profile elements and is defined by

$$WDc = \frac{1}{N} \cdot \sum_{k=1}^{N} \Delta z_k \,, \qquad [4]$$

at which Δz_k is the height of one profile element in the WD-Profile (figure 8).

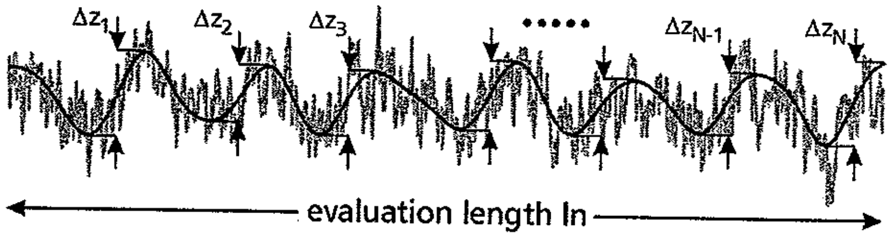

Figure 8: Parameter WDc: Mean value out of the vertical differences of the highest and the lowest points of the profile elements within the measured length.

The third parameter of the WD-Profile is WDt. It indicates the difference between the highest and the lowest profile point within the evaluation length in the WD-Profile (figure 9).

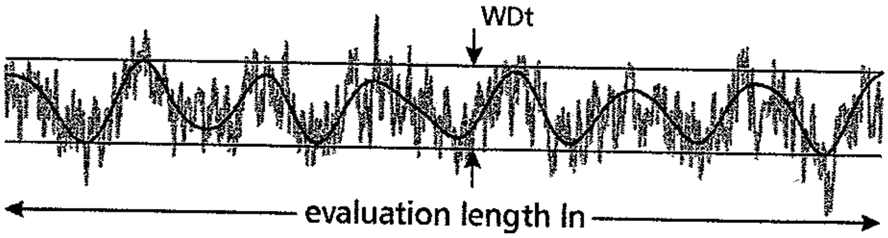

Figure 9: Parameter WDt: Vertical difference between the highest and the lowest profile point within the evaluation length.

3.4 Types of "dominant waviness"

With the procedure of "dominant waviness" at most two not harmoniously related periodic form deviations are detected. The amplitude spectrum of a turned profile for example displays harmonic components whose wavelengths amount to many times over the ground wavelength (namely the feeding rate of the cutter). Such harmonic frequencies are taken into account by the algorithm and are not considered.

The first and second "dominant waviness" contain the abbreviations WD1 resp. WD2. Are two dominant waviness' detected, the greater waviness will always be contained in WD1, that means with the greater parameter for WDc.

Waviness analysis always distinguishes three possible cases of characterization. Case 1 is a profile without periodic form deviation. That means no dominant waviness is detected and WDSm=WDc=WDt=0 applies. An example for such a profile is plotted in figure 10. The second case describes a profile with exactly one dominant periodic form deviation as seen in the centre of figure 10. The algorithm calculates according to the detected wavelength WDSm a WD-Profile and describes it by the parameters WDc and WDt. A profile with two dominant form deviations is plotted down in figure 10.The first "dominant waviness" describes here the manufacturing process machining. By monitoring the parameters cutting tool wear can be documented over the lifetime. The second dominant periodic form deviation occurs here as long wave form deviation, indicates perhaps a fault in the manufacturing process.

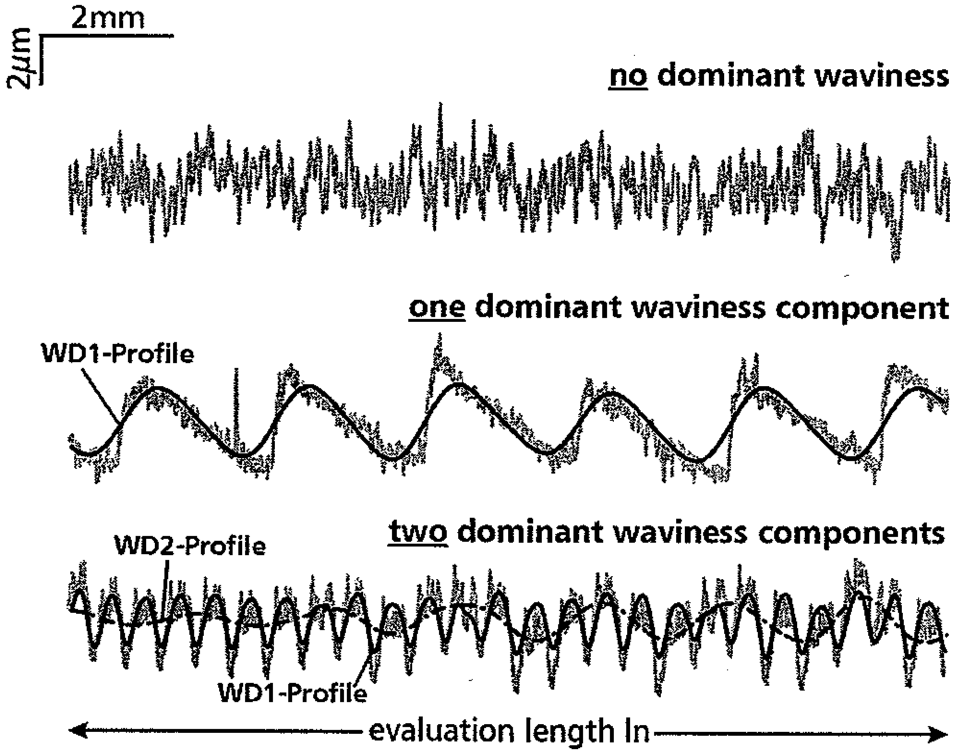

Figure 10: A surface profile can contain zero, one or two dominant waviness. Accordingly there is no WD-Profile, one WD1-Profile (continuous line) and one WD2-Profile(dot-dash line).

4. Drawing Specifications

Drawing specifications concerning the "dominant waviness" are geared to the range of wave length that is critically for functionality. Also the tolerable vertical characteristics of waviness are considered. The design engineer can choose between two different approaches for the tolerancing of "dominant waviness":

- "dominant waviness" is allowed up to an upper limit,
- "dominant waviness" is allowed up to a certain degree within a range of the period length specified by lower and / or upper bounds.

The basic drawing specification allows the evaluation of waviness within the entire range of the wave length of $0.02 \text{ mm} \leq \lambda \leq ln/5$. The evaluation length ln is taken from DIN EN ISO 4288. In this case WDc ≠ 0 respectively WDt ≠ 0 applies. However, as a rule, the design engineer ought to define the limit of the wave length as a matter of functionality. Therefore, it must be an exception, if the limit of the wave length is chosen according to DIN EN ISO.

If the period length is restricted to an upper wave length of 1.2 mm, then the drawing specification is

upper limit of period length		number of periods		parameter	upper limit of parameter
1,2	x	5	/	WDc	1,6

for profiles with a "dominant waviness" of WDc = 1.6 µm.
Per definition the evaluation length is five times the specified period length of 1.2 mm. The lower bound of the period length still is 0.02 mm.

The next example is to show how the period length can be bounded within the range of 0.3 mm ≤ λ ≤ 1.2 mm. Again the "dominant waviness" WDc is 1.6 µm. Drawing specification:

lower limit of period length		upper limit of period length		number of periods		parameter	upper limit of parameter
0,3	-	1,2	x	5	/	WDc	1,6

More examples of drawing specifications, their meanings, and possible measurement results are provided in table 1.

Drawing Specification	Meaning	Example		
WDc 3 measuring length according to DIN EN ISO 4288	WDc must not exceed 3 µm within the entire range of the period length.	WDc WDSm	2,68 / 1,68 µm 0,74 / 1,83 mm	✓
		WDc WDSm	3,32 / 0,00 µm 0,82 / 0,00 mm	⊘
2,5 x 5 / WDt 2,5	WDc must not exceed 2.5 µm within a period length of up to 2.5 mm.	WDt WDSm	1,82 / 0,00 µm 0,74 / 0,00 mm	✓
		WDt WDSm	2,81 / 1,79 µm 0,57 / 1,95 mm	⊘
		WDt WDSm	1,40 / 0,00 µm 0,84 / 0,00 mm	✓
0,3-1,5 x 5 / WDc 2	WDc must not exceed 2 µm within a period length ranging from 0.3 up to 1.5 mm.	WDc WDSm	1,91 / 0,00 µm 0,62 / 0,00 mm	✓
		WDc WDSm	2,36 / 1,12 µm 0,24 / 1,38 mm	✓
		WDc WDSm	2,39 / 0,00 µm 0,92 / 0,00 mm	⊘
0,8 x 16 / Rz 3 0,2-2,5 x 5 / WDc 1,5	Rz: The measuring length is ln = 12.5 mm. The limit of the wave length of the filter is lc = 0.8 mm. Rz must not exceed 3 µm. WDc: WDc must not exceed 1.5 µm within a period length ranging from 0.2 up to 2.5 mm.	Rz WDc WDSm	2,47 µm 1,22 / 0,00 µm 1,63 / 0,00 mm	✓
		Rz WDc WDSm	2,29 µm 1,82 / 1,22 µm 1,08 / 1,63 mm	⊘
		Rz WDc WDSm	2,36 µm 1,82 / 1,22 µm 0,18 / 1,63 mm	✓

Table 1: Examples of drawing specifications concerning "dominant waviness".

5. Examples

The "dominant waviness" is illustrated using two exemplary profiles. At first, the P-Profile of a turned surface is given in figure 11. Besides the grooves the profile is also superposed by a long wave signal. The evaluation according to DIN EN ISO 4288/4287 requires a wave length of $\lambda c = 0.8$ mm for the calculation of the W-Profile provided in the middle of figure 11. The evaluation according to the "dominant waviness" results in the WD1-Profile at the bottom of figure 11. In contrast to the W-Profile the WD1-Profile only contains the periodic fraction of the P-Profile.

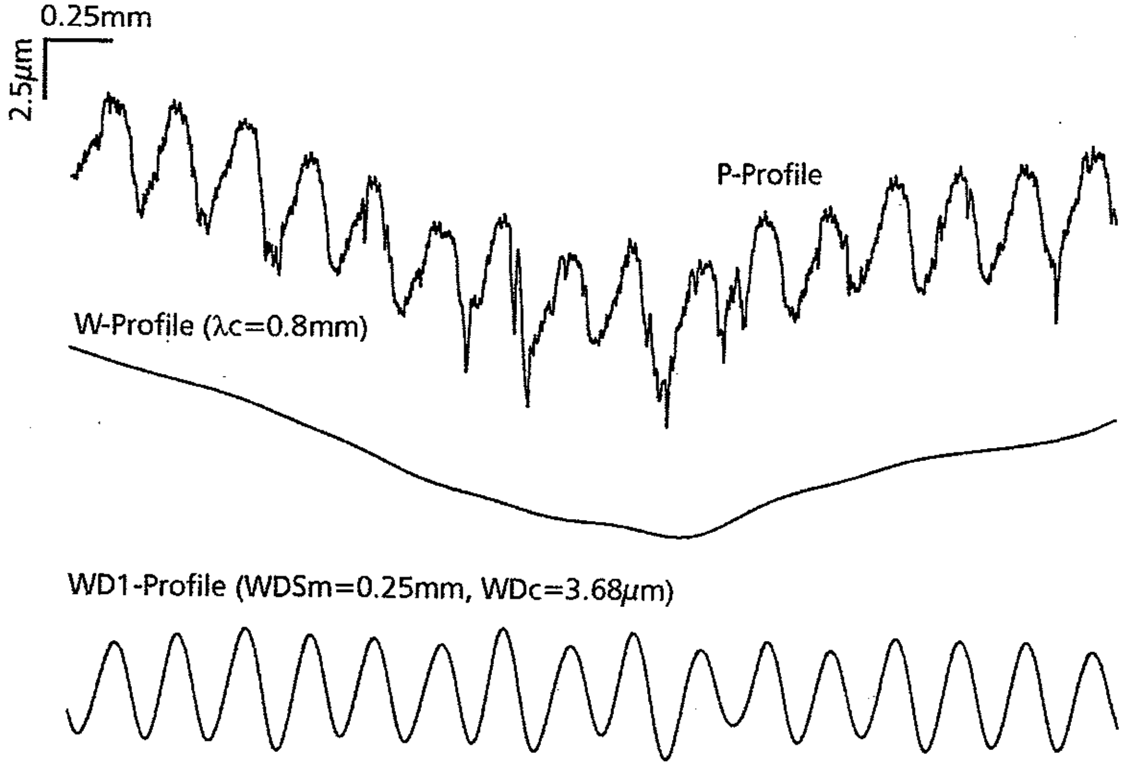

Figure 11: Top: P-Profile of a turned surface. Middle: W-Profile according to DIN EN ISO 4288/4287 with $\lambda c = 0.8$ mm. Bottom: WD1-Profile according to "dominant waviness".

A second P-Profile of a milled surface is given in figure 12. In this case, the evaluation according to "dominant waviness" provides two different dominant periodic fractions of the profile. The WD1-Profile is correlated to the feeding rate of the milling cutter. Thus, it characterizes the feed of the cutting plates. On the other hand, the WD2-Profile might indicate a non - conformance of the manufacturing process. The cause for the second "dominant waviness" might be a vibration of the work piece or the machine tool, for instance.

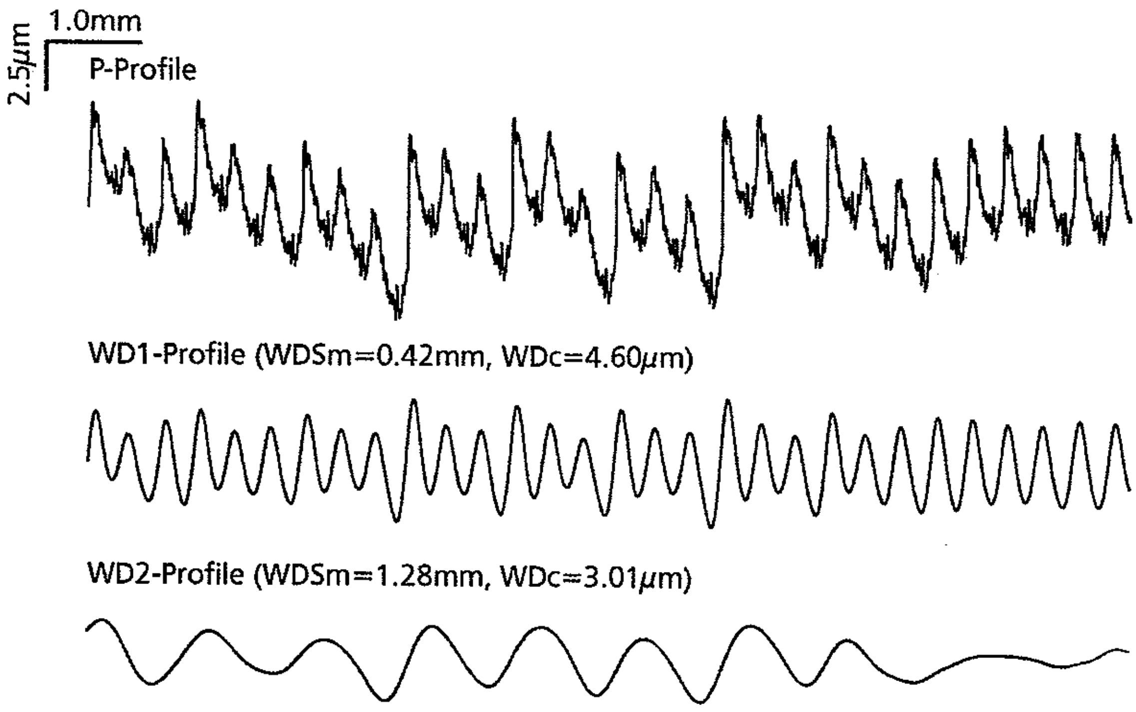

Figure 12: Top: P-Profile of a milled surface. Middle/Bottom: WD1-Profile and WD2-Profile according to "dominant waviness".

6. Summary

The method of "dominant waviness" facilitates well aimed detection of periodic form deviation within a given wave range of 0,02 mm $\leq \lambda \leq$ ln/5 (ln = evaluation length). The evaluation takes place independent of the character of the roughness, and is not systematically specified by a certain wavelength grid such as being the case with conventional waviness analysis according to DIN EN ISO 4287/4288. The result of the evaluation is a new kind of profile called the WD-Profile, determined by three parameters. Following DIN EN ISO 4287, WDSm describes the mean width of the profile elements and therewith the average wavelength of the WD Profile respectively the periodic form deviation. WDc is a vertical parameter. It represents the average height of the profile elements of the WD Profile. WDt after all describes the maximum height of the WD Profile within the evaluation length. Measuring- and evaluation conditions are defined in the guideline VDA 2007. The "dominant waviness" is especially suitable for evaluation of surfaces with functional behaviour affected by periodic form deviation.

7. References

VDA 2007: Geometrische Produktspezifikation – Oberflächenbeschaffenheit - Definitionen und KenngOrößen der dominanten Welligkeit. 2003.

ISO 4287: Geometrical Product Specifications (GPS) – Surface texture: Profile method – Terms, definitions and surface texture parameters. 1997.

ISO 4288: Geometrical Product Specifications (GPS) - Surface texture: Profile method – Rules and procedures for the assessment of surface texture. 1996-8.

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