Parameters and measurands in precision nanometrology

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On the basis of geometrical product specifications and verification, the importance of metrology has been continuously increasing to inspect and enhance high-tech manufacturing industry and to test high precise surfaces since the 1970s. Soon afterwards, the concept of precision engineering developed as a major trend in instrumentation and metrology through the technological advances in the field. For the desired quality determination, it is of crucial importance to measure the surface roughness defined by two traditional surface texture parameters: roughness average R_a and maximum height of profile R_z. In this study, the surface roughness analyses were also given for some precise surface structures for several roughness parameters, but R_a and R_z parameters giving us much of the idea on the surface structure were concentrated.

As the emphasis of nanotechnology increases, the use of microscopic metrology instruments must keep pace. The area of surface metrology was dominated by interferometers and contact profilometers, but as technologies have advanced there has been a need for a more flexible and complete solution. Taking into the consideration the drawbacks in contact approaches, the need and the importance for contactless techniques becomes evident. The latest generation of optical systems fills the need by providing direct surface roughness data.

In the experimental part of this study, the roughness values from stylus profilometer were compared with those from the infinite focus and confocal laser scanning type microscopes due to their respective capabilities. In conclusion, the problem with fine machined samples is that contact system cannot detect the extreme values of the surface due to the fact that the tactile extraction suppressed the details of the profiles which are smaller than the diameter of the stylus tip, whereas optical systems can detect precise value of the profile. There became substantial differences in values between the contact and the optical systems.

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NOMENCLATURE

GPS = Geometrical Product Specification and Verification
SPM = Scanning Probe Microscopy
R_a= Average roughness of the profile
R_z = Average maximum height of roughness profile
ISO = International Organization for Standardization
3D = Three – Dimensional
RMS = Root Mean Square
R&D = Research and Development

1. Introduction

The development of continuously decreasing workpiece tolerances lies in the same line with the perspective of nanotechnology. To fulfill metrological demands since about 1982 new high resolution and high precision measuring devices have been developed [1].

The study area of the Geometrical Product Specification and Verification (GPS) has standardized as a necessity with the globalization of the market worldwide, where the outsourcing of productions is still increasing continuously. When companies, subcontractors as well as entrepreneurs in geographically different fields powerfully count on outsourcing it becomes difficult for them to retain full control over the operations.

Increases in the quality of products are not to be joined of course exclusively with increase in the accuracy but up to a certain extent correlation is given, particularly if considered on the technical development during the last century [2,3]. This trend develops continuously further on because of the general development from micro technology to "nanotechnology" under which particularly special measurement techniques and production methods are to be implemented for the manufacturing accuracy in the nanometric scale [4,5].

Today the major challenges in manufacturing industry are able to increase productivity, decrease costs, and sustain high product quality at the same time. Improving the product quality with minimum production cost is of highly importance for companies, especially with the fierce world market competition [6]. The surface roughness is a very crucial aspect for designing mechanical elements and is also presented as a quality indicator of manufacturing process [7]. Present methods and processes cannot suffice demands of the unceasingly developing manufacturing.

2. Precision Nanometrology

Precision metrology has a long history tracing back to the inventions of the micrometer (J. Watt 1772), gage block (C. Johansson, 1896), interferometer (A. Michelson 1881), etc. It established the foundation for the Industrial Revolution and contributed greatly to modernize industries based on interchangeable manufacturing.

The term “precision” the best reflects the nature of precision metrology, which is often related to the ratio of resolution/accuracy to range. Nowadays, precision metrology is still playing an important role in precision manufacturing, especially due to its ability to make a wide range of measurements. However, it is difficult for precision metrology to reach a measurement resolution/accuracy better than 100 nm with current technology (Figure 1), which is required by nanomanufacturing. On the other hand, nanometrology, represented by scanning probe microscopy (SPM), is a relatively new measuring technology having only been developed since the 1980s. It can reach a high measurement resolution, down to 0.1 nm. As shown in Figure 1, however, nanometrology also cannot satisfy the requirement of nanomanufacturing because the measurement range of nanometrology is typically limited to 1 μm (Working Group on Dimensional Metrology of the Consultative Committee for Length, 1998). In addition, most of the commercial SPM instruments are for qualitative imaging use but not precise enough for quantitative measurement.

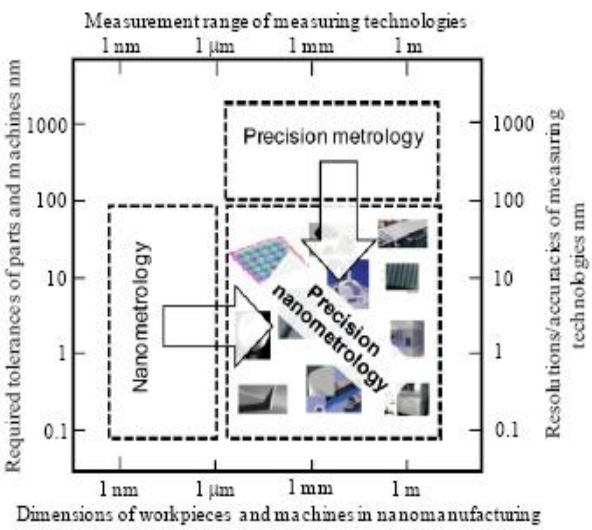


Fig. 1 From precision metrology and nanometrology to precision nanometrology [8]

With scanning tunneling and atomic force microscopes lateral resolutions up to 10 nm and in vertical direction up to 1 nm are achieved. So these measuring devices achieve a ratio of resolution of nearly 1 nm (Figure 2) showing an important advance over the above mentioned conventional methods [9].

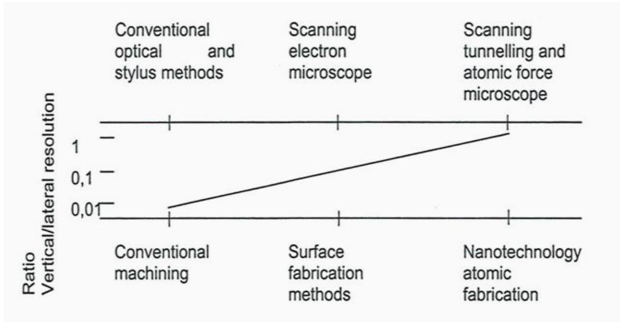


Fig. 2 Development of resolution ratio [10]

Form and function of the workpieces in the range of nano-metric differ from conventional parts in mechanical systems. Measurement standards are required written standards to be included in a format of ISO/TC 213 Geometric Product Specification and Verification (GPS), but the enclosed guidelines developed for macroscopic measurements do not fit to nanometrology. It is still not clear which functional parameters in nanometrology have to be tolerated. Definitely, new parameters and measurands for nanometrology have to be invented. The capability of a production process is dependent on the spread of the process and also on the uncertainty of the measurement process. The higher the measurement uncertainty is the narrower the spread of the production process has to be to maintain a specified tolerance.

2.1 Stylus and Optical Methods for Measurement of Surface Texture

Contact measurement methods assess surface finish by means of stylus type devices. While tactile devices have been being used for several decades, there has been instantaneously change direction towards optical non-destructive 3D metrology devices [11]. The contact roughness measurement of the machined metal surfaces was performed by the Form Talysurf Intra 50 profilograph with μltra software (FTS Iμ) illustrated in Figure 3 according to the ISO 4287. The surface roughness was analysed by mapping the readings taken in a direction perpendicular to the direction of lay by calculating of the parameters R_a and R_z from a standard spectrum of roughness.

The reason of the choosing of the steel balls is that they have very fine surfaces. The aim of this application was to see the differences between the methods, which are contact and non-contact, when measuring fine surfaces, because it is only when such surfaces are being measured that the differences are significant.

In the surface profiling technique, if the slope of a surface texture feature has a steeper angle than that of the half angle of the side of a conical stylus tip, then it will lose contact with the profile, having the same effect as a re-entrant angle on the resulting measurement.

The stylus traverses the surface peaks and valleys, and the vertical motion of the stylus is converted to an electrical signal by means of a transducer. The analysis may be done using analog or digital techniques. Stylus profilometer generates quantitative profile outputs of the surface under measurement [14]. Figure 3 illustrates the schematic diagram of the measurement of spherical samples.

In this experimental study, inspection and assessment of surface roughness of machined workpieces have been shown surface analyses using the results of stylus profilometer, using a stylus to feel the surface and optical measurement instruments which use an optical beam to scan the surface.

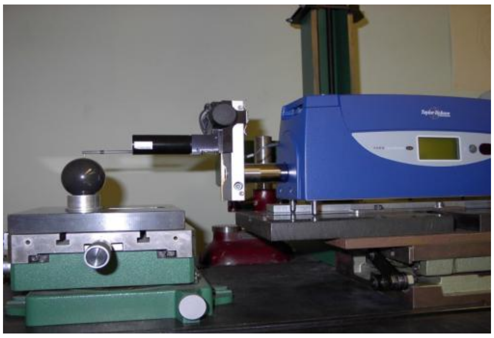


Fig. 3 Schematic diagram illustrating the measurement of spherical samples used in the experimental study [14]

Stylus profilometer, a scanning type confocal laser microscope and infinite focus microscope are commonly used instruments in the field of precision nanometrology.

Stylus profilometer has some advantages. The investment cost of the instrument is low and it is widely used. The stylus instrument is a versatile surface measuring technique. The main drawback of the contact stylus type measurement method is that the loaded stylus can damage or scratch the surface being measured, especially on soft surfaces [13]. The transducer and stylus tips are often fragile, hence the instrument must be applied in a fairly vibration free environment. Tips are required to be replaced and are not able to penetrate deep into the grooves owing to its nose radius. This direct measurement method does not extract roughness data from every point on the profile yet count on the stylus tip radius. That is to say; tip size limits measurement's bandwidth. Eventually, this technique is not convenient to be used on a test object undergoing a machining process simultaneously [15]. The main drawbacks of the stylus-based surface measurement technique make it necessary to develop non-contact optical methods that can be used for in-process, on-line and real time measurement [16].

The measuring principles used in optical surface metrology include optical focusing profilers, confocal point measuring and areal measuring sensors as well as interferometrical principles such as white light interferometry and speckle techniques. In comparison with stylus instruments optical techniques provide certain advantages such as a fast data acquisition, applicability in-process or contactless measurement. Additionally, optical sensors are commonly more influenced by critical geometrical conditions, optical properties of the object and the properties of the light source.

A scanning type confocal laser microscope has high resolution and high contrast. Optionally, a scanning type confocal laser microscope may have drastically enhanced resolution in light axis direction through confocal optics. The scanning type confocal laser microscope, sophisticated optical system, provides outstanding image resolution for operation at 408 nm by minimizing the aberrations associated with short wavelength illumination and maximizing the 408 nm light source performance and with a high vertical resolution down to 20 nm [18,19]. Current instruments have the light source with 405 nm wavelength. The scanning type confocal laser microscope is able to provide a new level of Z resolution as well. Confocal microscopes use focal depth. Confocal optics are designed to have almost infinite small depth of focus. That's why, not only the variation of focus, but also the absolute maximum value is analysed. The scanning type confocal laser microscope targets laser beam at a very small spot with objective lens and scans over the specimen in X-Y directions. It then captures the reflected light from specimen with detector and outputs the image of specimen on monitor (Figure 4)[14].

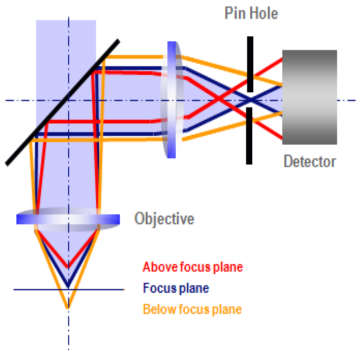


Fig. 4 Schematic representation of the principle of a scanning type confocal laser microscope [14, 18]

The infinite focus microscope (IFM) is used to build true color 3D images of surfaces and microscopic structures. Its operating principle combines the small depth of focus of an optical system with vertical scanning in order to provide topographical and color information from the variation of focus. The system delivers dense measurements over large areas with a density of 2-25 Mio measurement points and a high vertical resolution up to 20nm [12].

3. Roughness Measurement of High Precise Surface Structures

The surface of an engineering component, or workpiece, can be thought of as the physical boundary between the workpiece and the surrounding environment. In general, surface and near surface region of workpieces are the beginning point for engineering failures through corrosion and erosion [15]. Surface roughness comprises surface irregularities with relatively small spacings that usually include irregularities resulting from the method of manufacture being employed in its creation. The irregularities include a memory effect as a result of the cutting action of the surface generator and the influence of the machine tool that effects its fabrication and they are considered within the limits that are conventionally defined, for example, within the specification of the surface sampling length [16].

The surface roughness R can be explained as the root mean square (RMS) amplitude of the surface irregularities. For a specific surface with a measured RMS roughness, it is known that the maximum peaks of the irregularities are about 5 x RMS roughness.

In this study, R_a and R_z parameters giving us much of the idea on the surface structure were focused on. R_z is more sensitive than R_a to changes on the surface as maximum profile heights are being examined rather than average of peaks and valleys.

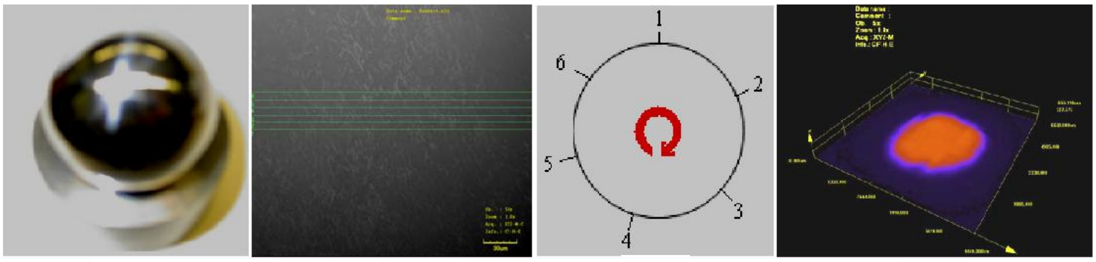
3.1 Roughness Measurements of High Precise Surfaces through Stylus and Optical Methods

The spherical surface plays an important role in precision engineering as they are used in precision machines and instruments. The method to be chosen to measure the roughness for the spherical surface is vital. In this experimental study, three devices were used to measure spherical specimens having high precision technical structures.

Six steel ball spherical samples were measured with three instruments. The surface structure of a sample and measured points (Figures 5a and 5b) and the schematic representation of the points on all spherical samples (Figure 5c) and the 3D image of the spherical sample (Figure 5d) are shown.

In the experimental part of this study, by the software of the stylus profilometer called "μltra", it is possible to analyse and monitor operations. The stylus arm with 60 mm length, conisphere diamond stylus tip size with 2 μm radius and 1 mN force (measuring speed = 0.5 mm/s) were used [17]. The stylus profilometer measures with a full gauge range of 1 mm and 16 nm vertical resolution [20].

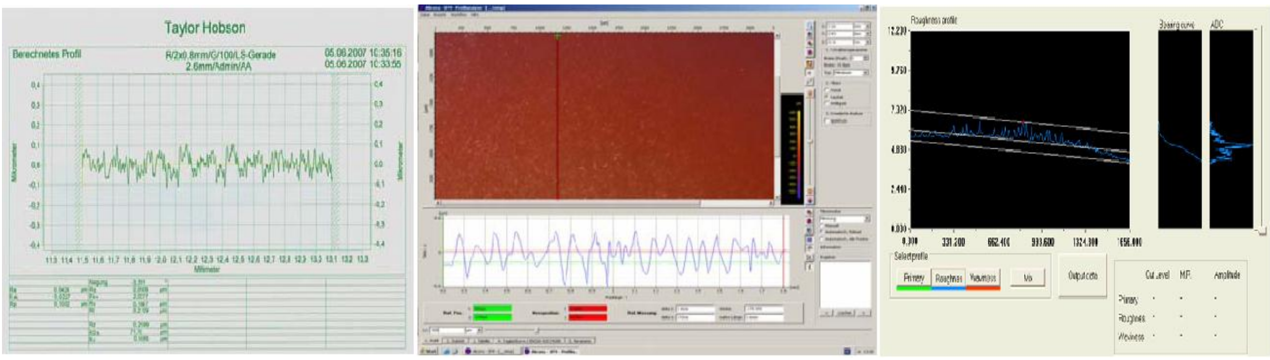
Gaussian filter in all measurements were used [14, 21]. During the process of measuring, the cutoff length was taken 0.8 mm and the sampling length 1.6 mm for spherical surfaces according to the ISO standards [22].



(a) (b) (c) (d)

Fig. 5 Steel Ball Sample (a), the surface structure of the steel ball sample and measured points on it (b) and the points taken from all measured spherical samples (c) and the 3D image of the spherical sample (d) [14]

For these steel balls having random surfaces, a standard high-pass Gaussian filter [18] with a long-wavelength cutoff of 0.8 mm was used to minimize long spatial wavelengths [21,23]. Roughness measurements of the spherical surfaces were made on six equally divided points specified in Figure 6c. The diagrams of roughness profile and values belonging to the sample taken from three instruments were obtained as shown in Figure 6. Comparisons of roughness values taken from three measuring systems, in terms of parameters R_a and R_z are given in Figure 7, where o1(optic1) is the abbreviation of the infinite focus microscope, c (contact) is the abbreviation of stylus instrument and o2 (optic2) is the abbreviation of the confocal laser scanning microscope.



(a) (b) (c)

Fig. 6 Diagrams of roughness profile belonging to steel ball sample respectively obtained from the stylus type system (a), the infinite focus microscope (b) and the confocal laser scanning microscope (c) [14]

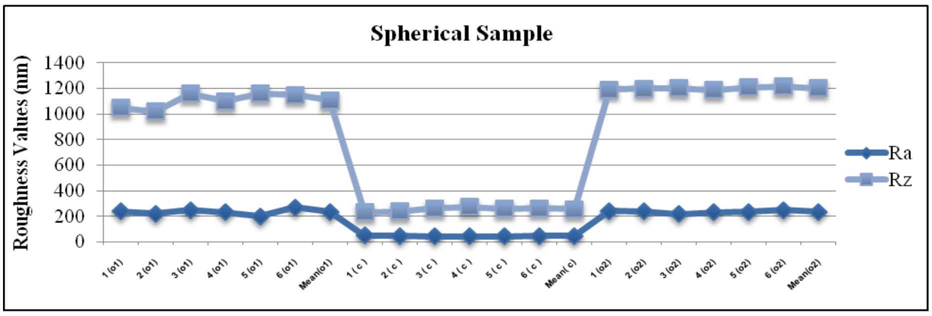


Fig. 7 Comparisons of the roughness values belonging to steel ball sample taken from the stylus and two optical measuring systems in terms of the parameters R_a and R_z [14]

The spherical samples were manufactured with surface roughness values ranged from 150-310 nm (R_a). The stylus tip size is 2 µm in radius. Thus, as expected from the manufacturing process of the samples, the measurement results of steel ball sample are noticeably small for a smooth finish. The stylus is not able to detect the smooth surfaces lower than its nose radius. These surfaces include the random roughness surfaces with R_a ranging up to 310 nm.

3.2 Statistical Results

The data obtained were evaluated by using SPSS 15.0 (Statistical Package for Social Science) and a One-way analysis of variance (Oneway ANOVA) was used (α =0.05) to test the significant difference between measurement systems. When the Oneway ANOVA was applied to test the equality of three instruments at one time by using variances (feed in mm, periodicity, type of material, contrasting, type of production process etc.), a comparison of them was done employing a Post-Hoc test to identify which groups were significantly different from others assuming a 95 percent of confidence level. These tests showed that there was a substantial difference in several roughness parameters selected for this study between the stylus measurement system and two optical measurement systems statistically. Figure 8 indicates the discrepancies between the values of roughness measurement obtained with the contact stylus profilometer and 3D optical measurement systems in terms of roughness parameter R_a.

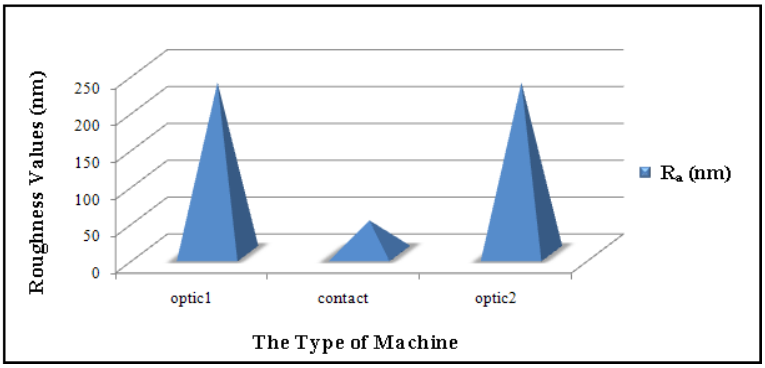


Fig. 8 The roughness measurements taken from the stylus profilometer and optical microscopes in terms of R_a [14]

In the experimental part of this study, the 3D parameters were also measured. For the evaluation of surface roughness, S_a, one of the most popular surface area roughness parameters was chosen for the comparison with R_a one of the most widely used 2D roughness parameters in surface texture measurement (Figure 9).

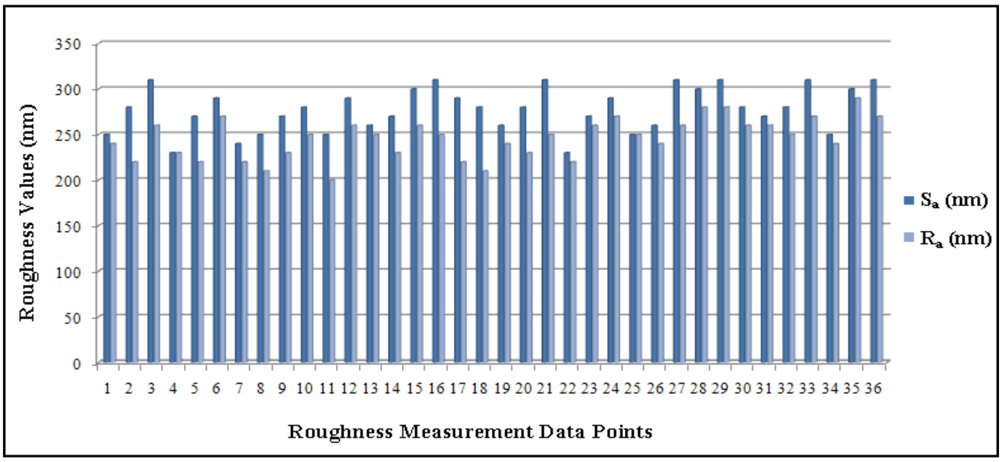


Fig. 9 The roughness measurements taken from the stylus profilometer and optical microscopes in terms of R_a [14]

As it can be seen from Figure 9, the measurement results for S_a turned out to be similar with those for R_a parameter, because R_a is the 2D counterpart of the 3D descriptor S_a. Both R_a and S_a reflect the arithmetic mean of the absolute values of the surface point departures from the mean plane within the sampling area [14].

4. Conclusions

In this paper, the concept of precision engineering and the technological advances in instrumentation and metrology have been discussed. Besides, the capabilities of three measurement systems were presented in terms of their similarities and differences. The major disadvantage of using a stylus instrument is that the instrument readings are based on a limited number of line samplings, which may not represent the real characteristics of the surface. This kind of deviation may cause serious errors in the surface quality assessment especially when the surface profile is periodic. The tactile extraction was performed with a sphere of a 2 μm radius. The tactile extraction suppressed the details of the profiles which are smaller than the diameter of the stylus tip and rounded off the peaks by the radius of the contacting spherical portion of the stylus. The tactile extraction causes an unavoidable smoothing of the profile which is often designated as mechanical filtration [24].

It is observed that three devices are giving comparable results if the surface has a good reflection value, isn't very fine machined surface with a periodic/random profile and not ruined or scratched.

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REFERENCES

1. Prostrednik, D. and Osanna, P. H., "Nanometrology for Industrial Applications," E&I Elektrotechnik und Informationstechnik, Vol.115, No.4, pp.213-217, 1998.
2. Kienzle, O., "Genauigkeitsansprueche des Konstrukteurs und ihre Verwirklichung durch die Fertigung," Industrieanzeiger, Vol. 82, No. 62, pp. 26-42, 1960.
3. Osanna, P. H., "Dreidimensionales Messen," Future 80, Frankfurt: Ingenieur-Digest-Verlag, pp. 216-218, 1980.
4. Taniguchi, N., "On the Basic Concept of Nanotechnology," Proceeding of International Conference on Production Engineering, Tokyo, Part 2, pp.18-23, Tokyo: JSPE, 1974.
5. Whitehouse, D. J., "Nanotechnology Instrumentation," Measurement + Control, Vol. 24, No.2, pp.37-46, 1991.
6. Zhang, H. Z., An, Q. L., Zhang, Y. S., Liu, G. and Chen, M. "Optimization of Surface Roughness by Uniform Design of Experiments in Milling of 1Cr18Ni9Ti," Advance Materials Research, Volumes 69-70, pp. 490-494, 2009.
7. Suresh, P.V.S., Rao, P.V. and Deshmukh, S.G., "A Genetic Algorithm Approach for Optimization of Surface Roughness Prediction Model," International Journal of Machine Tools and Manufacture, Vol.42, No. 6, pp. 675-680, 2002.
8. Gao, W., "Precision Nanometrology: Sensors and Measuring Systems for Nanomanufacturing", ISBN: 978-1849962537, Springer Publishing, 2010.
9. Durakbasa, M. N., "Geometrical Product Specifications and Verification for the Analytical Description of Technical and Non-Technical Structures", printed in Austria (TU Wien: Abteilung Austauschbau und Messtechnik), ISBN 3-901888-26-8, pp. 27, 2003.
10. Whitehouse, D. J., Nanotechnology Instrumentation – Measurement + Control, Vol. 24, No. 2, pp. 37-46, 1991.
11. Jiang, X., Scott, P. J., Whitehouse, D. J. and Blunt, L., "Paradigm shifts in surface metrology; Part II; The current shift," In: Proceedings of the Royal Society, Vol. 463, No. 2085, pp. 2071-2099, 2007.
12. http://www.alicona.com
13. Vorburger, T.V., Rhee, H.-G., Renegar, T.B., Song, J.-F. and Zheng, A., "Comparison of optical and stylus methods for measurement of surface texture", International Journal of Advanced Manufacturing Technology, Vol. 33, Numbers 1-2, pp.110-118, 2007.
14. Demircioglu, P., "Comparison of Stylus and Optical Methods: Evaluation of High Precision Surface Structures and their Mathematical Modeling with the Help of Statistical Techniques," LAP LAMBERT Academic Publishing, Germany, ISBN: 978-3838390215, pp.121, 2010.
15. Tay, C.J., Wang, S.H., Quan, C. and Shang, H.M., "In situ surface roughness measurement using a laser scattering method," Optics Communications, Vol. 218, Numbers 1-3, pp. 1-10, 2003.
16. Persson, U., "Surface roughness measurement on machined surfaces using angular speckle correlation," Journal of Materials Processing Technology, Vol.180, Numbers 1-3, pp. 233-238, 2006.
17. DIN EN ISO 4287:2009, Geometrical Product Specifications (GPS) - Surface texture: Profile method - Terms, definitions and surface texture parameters (ISO 4287:1997 + Cor 1: 1998 + Cor 2: 2005 + Amd 1: 2009)
18. http://www.microscopy.olympus.eu/microscopes
19. Afjehi-Sadat, A., Durakbasa, M. N., Stout, K. J., Osanna, P. H. and Ruiz, J. M.: "Measurement of surface roughness, waviness and the primary profile," In: Measurement in Technology. A textbook from the multimedia courseware METROMEDIA-ONLINE, Volume 2, Vienna, ISBN 80-89112-05-6, pp. 382-403, 2005.
20. http://www.taylor-hobson.com
21. Durakbasa, M. N., Osanna, P. H. and Demircioglu, P., "The Factors Affecting Surface Roughness Measurements of the Machined Flat and Spherical Surface Structures – The Geometry and the Precision of the Surface," X. International Symposium on Measurement and Quality Control 2010, pp.119, Osaka, Japan, Sep 5-9, 2010.
22. American Society of Mechanical Engineers, ASME B46.1:2002 Surface texture, surface roughness, waviness and lay, NJ, USA.
23. Blateyron, F., "New 3D Parameters and Filtration Techniques for Surface Metrology", Quality Magazine White Paper, Digital Surf, France, 2006.
24. Demircioglu, P. and Durakbasa, M. N., "Investigations on Machined Metal Surfaces through the Stylus Type and Optical 3D Instruments and their Mathematical Modeling with the Help of Statistical Techniques", Measurement, Vol. 44, No. 4, pp. 611-619, 2011.