Paper:

Evaluation of the IWF-Wunder Reproduction Method for Generating Positive Replica

Marcel Henerichs, Michael Egeter, Thomas Liebrich, Robert Voß, and Konrad Wegener

Institute of Machine Tools and Manufacturing (IWF),
Swiss Federal Institute of Technology Zurich (ETH)
Tannenstrasse 3, 8092 Zürich, Switzerland
E-mail: {Henerichs, Liebrich, Voss, Wegener}@iwf.mavt.ethz.ch, Egeterm@student.ethz.ch
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Research into manufacturing technology requires regular measurement and documentation of workpiece and tool quality. The instant or direct measurement of tool or workpiece surfaces is often difficult or impossible. Remounting of workpieces or tools leads to undesired remounting errors, a direct integration of adapted measurement systems is not suitable for research and development. Additionally, abrasive or transparent surfaces can be unsuitable for use with some measurement systems. This study evaluates an imprinting method for the production of positive replicas of tool or workpiece surfaces. The resulting errors between original sample and replica are evaluated. The analyses include common test methods, such as tactile surface profiling, focus variation microscopy, and white light interferometry. The study shows that for the evaluated reproduction method, the difference between original and replica is less than 10% of the surface roughness, R_a, for original surface roughnesses greater than $R_a = 0.1\mu$m. Mostly better results are achieved (difference $< 2\%$). In addition, contour dimensions greater 1 mm can be copied with deviations less than 0.5%.

Keywords: positive replica, degree of resemblance, thermosets, measurement technology

1. Introduction

Research and development in manufacturing regularly evaluates new prototypes and new processes. Measurement of prototype parts and tools typically takes place in rooms with highly controlled environmental conditions, and with commonly used metrological devices. In-process measurements face additional difficulties. Measurement between different manufacturing steps is often not possible or leads to new problems. For example, remounting errors can occur if the workpiece or tool needs to be removed between roughing and finishing. In this case, the metrological devices would have to be mounted directly on the machine tool. This adaption is mostly favorable for series production, but difficult and expensive to implement in research, due to the constantly changing process conditions.

Extensive and regular quality analyses during manufacturing in research applications can lead to low production efficiencies: transport and remounting among the various measurement devices and machine tools are required. Furthermore, machine tool and measurement devices need to be available at the same time. Heavy or large samples often cannot be mounted on measurement devices or require an adaption. Difficult-to-access surfaces, such as the wall of a bored hole or undercuts, can require the destruction of the workpiece for the measurement. Ultra-hard materials, such as diamond or cubic boron nitride, cause accelerated wear on tactile measurement systems. In addition, the semi-transparency of materials like diamond or glass makes the application of optical measurements difficult.

Positive replicas are able to avoid the above-mentioned problems; therefore, the positive replica must meet the required precision. Additionally, the replica material needs to either possess sufficient hardness for use with a tactile measurement device or meet optical requirements of the associated measurement systems. Such a reproduction method was developed by Wunder and Vargas [1-3]. In their studies the authors required efficient analyzing solutions for engineered grinding tools, including grinding wheels or honing tools, for example. Engineered grinding tools possess diamond grains 100-400 μm in diameter that are brazed to the tool body. The analysis of the wear patterns on the single diamond grains was of primary interest. Additionally, neither optical nor tactile measurements of these highly abrasive and transparent grains could be conducted. The authors required an imprint technology which enabled measurements from within the machine tool. The negative imprints needed to be taken independent of the tool orientation. Additionally, all geometric features, including undercuts, had to be reproduced and short imprint curing time was preferred; the curing time of the positive replica was of secondary importance. The shrinkage during curing needs to be as low as possible, during each stage of the process. The authors tested different viscosity and material combinations until they found a precise system for a positive replica design that can be analyzed using optical and tactile systems. Negative copies of parts are generated by silicone imprints. On this basis, positive replicas are made by casting the negative form with epoxy.

The presented study evaluates roughness, and form, position, and dimensional deviations between original and replica components. Surface replication based on casting is employed for quality control purposes following two main routes described by Hansen [4]. For qualitative surface inspection (A), surfaces are checked but not measured. Examples therefore are metallographic inspections or wear analyses of grinding tools. The other route followed involves quantitative topographical measurements (B), e.g., surface roughness measurements. The difference between (A) and (B) is that measurement technology is used to obtain quantitative results.

2. State of the Imprint Technology

The method developed by Wunder [1] (further referenced as IWF-Wunder) uses polyvinyl siloxane to create negatives. Additionally, IWF-Wunder generates a positive replica made from polyepoxide (epoxy). The application of the reproduction method for wear inspection (A) has already been evaluated in previous research [1]. Wunder analyzed a grinding process with engineered grinding tools [3]. Wunder found that the grinding process is significantly influenced by the wear pattern of the single grains. In the current study, a detailed determination of the diamond grain wear of these cutting tools with undefined cutting edges is required, and positive replicas of the grinding wheel surface have been manufactured. The evaluation compared the amount of tool wear on both, the original and replica surfaces. Good suitability for this wear analysis is validated.

Many technologies have been developed to generate imprints and positive replicas. Most technologies have been developed for mass production applications, such as metal casting and plastic molding [4]. These methods typically modify the material properties using high temperatures, transforming metal, glass or plastic from a fluid or viscous state to a solid state for the creation of the imprint [5-10]. Replication methods at shop floor conditions need to work at or close to room temperature. Additionally, the creation of an adapted tray for the negative imprint material in research applications needs to be simple, as only a limited number of samples of the same dimensions is to be produced. Most authors and companies recommend using thermoset materials for such applications [11-14]. A chemical reaction leads to an irreversible solidification of the thermoset material. Depending on the modification of the thermoset, the reaction can occur at room temperature. Main materials used are polyepoxide (epoxy) and polydimethylsiloxane (PDMS) [4].

Replication for surface inspection, especially regarding surface roughness, has been analyzed extensively. Meanwhile most research focuses on the replication of metal [15, 16]; other research focuses on different materials like wood [17]. In scientific metallographic research an error margin of 6% is typically achieved [4]. Commercially available systems using a PDMS base focus on maintaining a short curing time for the negative imprint for efficient research [13, 14]. The systems combine a structure resolution of approximately 0.1 μm and a low shrinkage coefficient. In the medical industry, the application of replica for measurement of specimen dimensions is well known. Similar to the presented method, in medical applications, imprints must be cured within five minutes, as the well-being of the patient is important. Chee and Donovan reviewed different systems for dental imprints [18]. The authors conclude an excellent impression quality of the polyvinyl siloxane. Like the IWF-Wunder method, most methods start with a "tray" for the polyvinyl siloxane made from a high viscosity (putty) material. The method is also used for dental imprints on fossils [12]. Analyses in the dermatology field focus on micro geometry features [19]. Imprints using a silicone resin have also been taken to analyze the influence of repeated sun exposure on human skin.

3. Evaluation Procedure

The authors' evaluation of the IWF-Wunder method aims to test the suitability of the reproduction method in typical manufacturing floor conditions. Meanwhile conducted in environmentally controlled rooms with specimens at room temperature, surface cleaning devices are used as available at a machine tool station. This includes gloves, compressed air, ethanol and acetone. The production of a positive replica is done using the following steps:

i. *Cleaning of the specimen surface with ethanol*
ii. *Production of a tray using high-viscosity (putty) material*
iii. *Hardening of the tray material*
iv. *Application of the negative imprint material on the specimen*
v. *Hardening of the polyvinyl siloxane*
vi. *Generation of a mold by adding additional walls to the imprint*
vii. *Casting of the negative mold with epoxy*
viii. *Deform of positive replica*

The physical properties of the used imprint and replica materials are listed in **Table 1**. The consistency is measured according to DIN EN ISO 4823.

The experimental design for quantitative topographical measurements (B) is two-fold: testing the capability of the IWF-Wunder process for (1) roughness measurements, and (2) for position, form, and dimension deviation measurements. Following this setup, two object types have been defined.

3.1. Type 1 Objects – Roughness Measurements

Seven roughness standards according to ISO 5436 have been selected. The ISO 5436 set is expanded by one ultra-precision ground workpiece having a profile roughness finer than $R_a = 0.01$ μm (see **Table 2** for data).

Table 1. Physical properties of imprint and replica material.

Analysing step	Putty carrier	Negative imprint	Positive replica
Material	Polyvinyl siloxane	Polyvinyl siloxane	Polyepoxide
Consistency	24 mm	42 mm	–
Viscosity	–	–	550 mPa
Working time at 20°C	2 min	2 min	30 min
Total setting time	4 min	4 min	12 hours
Hardness [Shore]	A60	A46	D78
Linear dimensional change [%]	−0.2	−0.2	–

Table 2. Type 1 Objects.

ID	Object	Manufacturing process	Nominal value
N01	Mirror	UP-Grinding	$R_a < 0.01\ \mu m$
N02	Standard Heidenhain (fine)	not representative	$R_a = 0.11\ \mu m$
N03	Standard Heidenhain (rough)	not representative	$R_a = 0.86\ \mu m$
N04	Standard Agie No.4	EDM	$R_a = 0.80\ \mu m$
N05	Standard Schlatter	Grinding	$R_a = 0.80\ \mu m$
N06	Standard Schlatter	Turning	$R_a = 3.20\ \mu m$
N07	Standard Agie No.7	EDM	$R_a = 3.15\ \mu m$
N08	Standard Heidenhain (middle)	not representative	$R_a = 0.31\ \mu m$

The sample N01 has been manufactured using the technology of Electrolytic In-Process Dressing (ELID) grinding [20-23]. The selected samples cover the major machining technologies, including cutting with defined and undefined cutting edges, as well as corrosive processes. The chosen bandwidths for surface roughness corresponds with typical values achieved in each of the machining processes.

The setup for profile measurements consists of three devices: (1) a tactile surface form profiler, Talysurf Series 2 (TSP)[1]; (2) an infinite focus microscope, Alicona[2] IFM G4 (IFM); and (3) a white light interferometer, Zygo[3] NV 5000 (WLI). The uncertainty of the TSP is U ($k = 2$) = 2% of the roughness value +4 nm; the manufacturers of the other devices does not give any explicit uncertainty values [24, 25]. Originals and replicas of all Type 1 Objects are measured on all three devices. The kinematic roughness of each sample is measured according to ISO 4287 and 4288. The evaluation length, $l_n = 5l_{ri}$, is measured three times for each specimen. The values for R_a and R_z of every specimen are calculated as the average of these three measurements. The average deviation in R_a between original and replica is taken to evaluate the replication accuracy. A deviation less than 10% is judged "sufficient," a deviation less than 5% is judged "good."

1. Manufactured by: Taylor-Hobson Ltd., Leicester, UK.
2. Alicona Imaging GmbH, Grambach, Austria
3. Manufactured by: Zygo Corp., Middlefield CT, USA.

Table 3. Type 2 Objects.

ID	Object	Comment
G01	Sandvik Cutting-Insert	backside w/o chip breaker
G01-A	Replica No.1	none
G01-B	Replica No.2	none
G01-C	Replica No.3	none

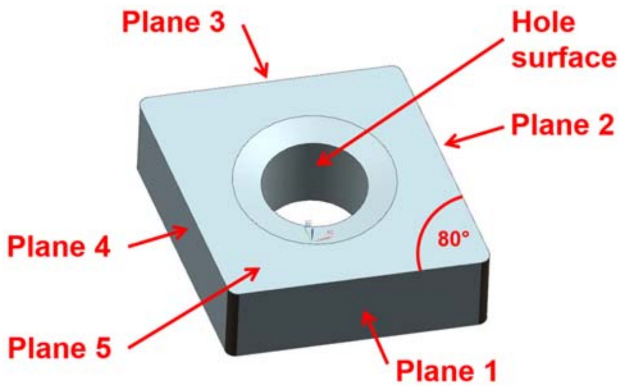


Fig. 1. Planes on Type 2 Objects.

3.2. Type 2 Objects – Form, Position, and Dimension Deviations

The evaluation of shape and form errors resulting from the imprint method is conducted using a cutting insert from Sandvik[4]. The cutting insert contains all required geometric features. The chosen model consists of tungsten carbide, allowing the measurement using tactile and optical devices. Parameters including measurement of clearance, wedge, and rake angle are also possible applications for the replication method. **Table 3** shows the four analyzed Type 2 Objects.

Object shapes of originals and replicas are measured using a coordinate-measuring machine (CMM), Leitz PMM 864, having a tip diameter of 2 mm. The uncertainty of the CMM is U ($k = 2$) = 1, 2 μm + L/400 for a single measurement point, according to ISO 10360-1:2000. Planes 1 to 4 are detailed using 35 points, and Plane 5 using 26 points (**Fig. 1**). Circles are measured using 20 points. The following deviations are measured on the original part, G01, and replicas A, B, and C (see **Figs. 1** and **3**).

- Flatness of Plane 1 to 5
- Parallelism and plane distance of Planes 1 to 3, and Planes 2 to 4
- Roundness and diameter of the hole at three different depths, with offset of 1 mm
- Angle of the Planes 1 to 4, relative to Plane 5
- Angle between Planes 1 and 2, as well as between Planes 3 and 4

4. Article code: CNMG 12 04, manufactured by Sandvik Coromant AB., Stockholm, Sweden.

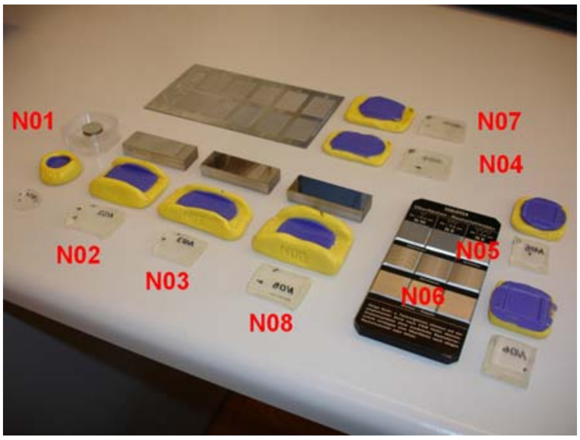


Fig. 2. Type 1 Objects – evaluation of surface roughness for original and replica.

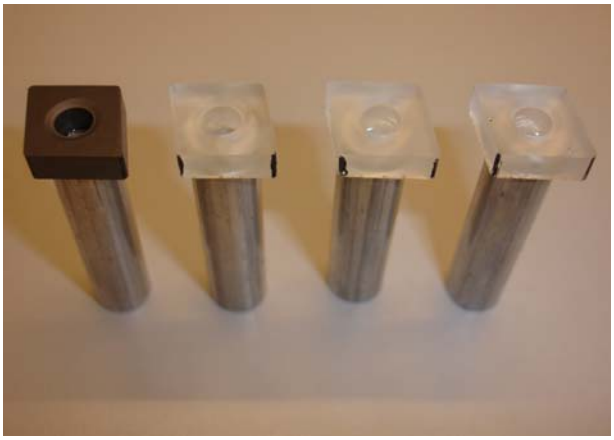


Fig. 3. Type 2 Objects – evaluation of form, position and dimension deviations for original and replica.

3.3. Object Overview

Figure 2 shows the objects, imprints and positive replicas of Type 1 Objects. The blue imprints are made of polyvinyl siloxane; the positive replicas consist of epoxy. The yellow trays shown consist of high-viscosity (putty) polyvinyl siloxane. The surface roughness of the original objects and the positive replicas is analyzed.

Figure 3 shows the object and the multiple positive replicas of the corresponding Type 2 Object. The deviations in the shape and form errors are measured using a CMM.

4. Capability of Method

4.1. Roughness Measurements

Figure 4 shows the resulting deviations for the different roughness standards of the Type 1 Objects. The specimens shown are sorted by the surface roughness and the periodicity of the specimen surface. Each sample is displayed with a total of three boxes. The first box shows the specimen name. The other two boxes show absolute deviations between original and positive replica. The second box shows the smallest achieved deviation and the measurement device, which achieved this smallest deviation. The third box displays the average deviation value for all three measurement devices. The specimen name and the average deviation are always highlighted in the same color. If the two boxes are highlighted in green, the average reproduction deviation is less than 5% and rated "good." If the deviation of the positive replica is less than 10% but not 5%, and is hence "sufficient," the specimen name and the average deviation are highlighted in yellow. Otherwise the boxes are highlighted in red. The same details apply to the second box. If the best measurement device achieves a deviation less than 5%, the box is green, below 10% yellow, otherwise the box is colored red.

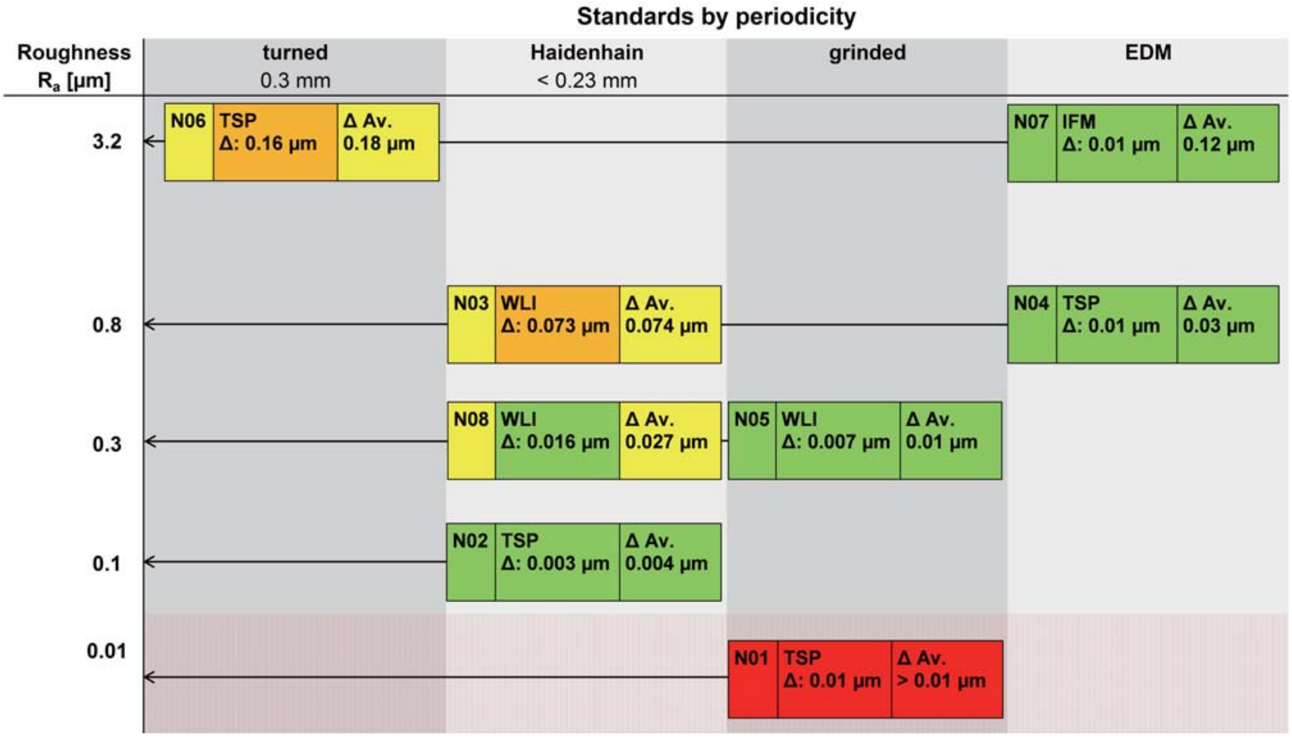
For $R_a = 3.2\ \mu$m the turned roughness standard N06 can be reproduced with an average deviation of 0.18 μm (5.5%), the lowest deviation, 0.16 μm (5.2%), is achieved using TSP. The specimen N07 being EDM machined achieves an average deviation of 0.12 μm (3.5%); the smallest deviation is achieved with the IFM being 0.01 μm (0.3%). For $R_a = 0.8\ \mu$m the Haidenhain roughness standard N03 is reproduced with an average deviation of 0.074 μm (8.9%), the smallest deviation is 0.073 μm (8.6%) using the WLI. The EDM machined roughness standard N04 with a value of $R_a = 0.8\ \mu$m shows an average deviation of 0.03 μm (2.8%), the lowest deviation is achieved by the TSP with 0.01 μm (0.9%). The Haidenhain surface roughness standard N08 with $R_a = 0.3\ \mu$m can be reproduced with an average deviation of 0.027 μm (8.3%). The lowest deviation occurs with the WLI being 0.016 μm (4.9%). The ground roughness standard N05 with the same surface roughness shows an average deviation of 0.01 μm (3.0%), with the lowest deviation being 0.007 μm (2.3%), achieved with the WLI. The Haidenhain roughness standard N02 with a surface roughness of $R_a = 0.1\ \mu$m is reproduced with an average deviation of 0.004 μm (3.9%). The best value is achieved using the TSP with a deviation of 0.003 μm (2.6%). The ELID-ground sample with a surface roughness $R_a < 0.01\ \mu$m can be reproduced with a deviation of 0.01 μm (286%) with the TSP, the WLI measures an even greater deviation.

For surface roughness values from $R_a = 0.1\ \mu$m to $R_a = 3.2\ \mu$m five of seven specimens reach a good replication quality, the other two specimens achieve a sufficient replication quality. The deviation decreases with greater specimen periodicity. In contrast to the findings of Tosello et al. [23] for this bandwidth of surface roughnesses, the deviation of the positive replica is independent of the surface roughness of the specimen.

Object N01 with a surface roughness $R_a < 0.01\ \mu$m produces replication results of insufficient quality. The object has a very smooth surface. The errors inserted during the reproduction process are too severe. A limit for the method seems to exist for values of the original part between $R_a = 0.1\ \mu$m and $R_a = 0.01\ \mu$m.

Figure 5 shows the singular results of the roughness measurements. The dots display the mean value of the

Fig. 4. Deviations of roughness measurements.



measurement for each device. The black bars show the total uncertainty of the measurement. The total uncertainty results from the uncertainty of the single measurement plus the deviation between the three measurements. The blue rhombi show the measured roughness of the original, the red squares display the measured roughness of the positive replica. N01, N02, N03 and N08 could not be measured using the IFM microscope because of the high surface transparency of the positive replicas.

In average the WLI achieves the lowest deviation between original and replica. The very smooth ELID-ground surface of the specimen N01 and its positive replica are challenging to reproduce and measure. The TSP measures a deviation of 0.01 μm (286%) for the R_a- and 0.05 μm (250%) for the R_z-values.

4.2. Form, Position and Dimension Deviations

Table 4 shows the results of the measurement for form, position and dimension tolerances for the Type 2 Objects. The measurement results include the original cutting insert and the average of the three positive replicas. The difference between these measurement results is displayed in absolute and relative values. The flatness deviation of Planes 1 to 4 of the original is 18.8 μm in average. The average flatness deviation of the positive replicas is 26.0 μm. The difference of the flatness deviation between original and replicas is for Planes 1 to 4 is 7.2 μm (38.1%). The flatness deviation of Plane 5 is 4.2 μm for the original. The positive replicas achieve an average value of 9.7 μm. This results in a difference of 5.5 μm (130.2%). The parallelism error between Planes 1 and 3 and Planes 2 and 4 is 61.2 μm for the original cutting insert. The positive replicas reach an average value of 76.0 μm. The results differ for 14.9 μm (24.3%). The cutting insert has an average roundness error for the circles 1, 2 and 3 of 10.0 μm; the three replicas achieve an average roundness error of 21.1 μm. The roundness error of the positive replica is thus 11.1 μm (111.3%) greater than the original. The IWF-Wunder method produces in general poor results for the measurement of form deviations (e.g. flatness). Differences exceeding 100% between the original value and the replica are observed. The position deviation (parallelism) on the replica produces a maximum error of 25% compared to the original. Main reasons are deformations on the micrometer scale of the (negative) imprint material during the curing process.

The plane distances of the Planes 1 and 3 as well as from the Planes 2 and 4 have been measured. The cutting insert shows an average distance of 12.721 mm, the three positive replicas show an average distance of 12.693 mm. The difference is 28 μm (0.221%). The average hole diameter of the cutting insert is 5.200 mm compared to 5.192 mm for the replica, resulting in a difference of 8 μm (0.149%).

Finally the angles between Planes 1 to 4 and plane 5 have been measured. The angle on the original cutting insert is 90.307° in average, meanwhile the measured angle for the positive replica is 90.191°, resulting in an error of 0.116° (0.128%). The angles between Planes 1 and 2 as well as Planes 3 and 4 are in average 80.086° for the original and 80.036° for the replica, resulting in an error of 0.049° (0.062%).

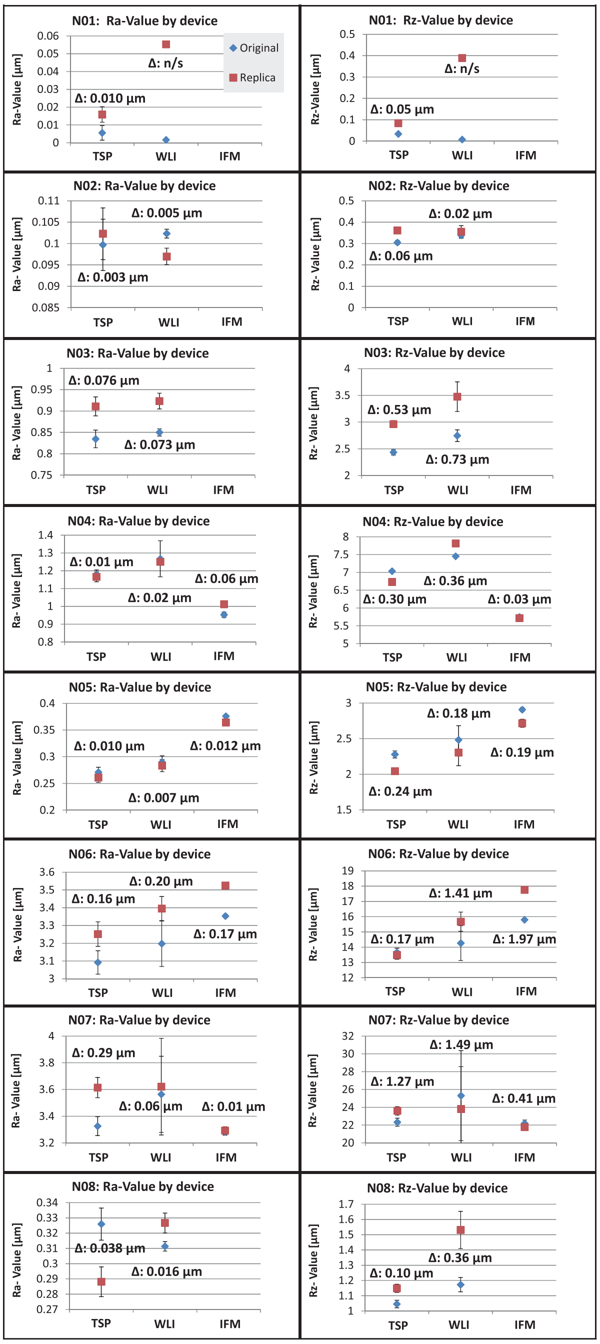


Fig. 5. Results of roughness measurements.

The influence of replication errors is related to their local expansion. The main errors occur during the generation of the negative imprint. These errors are on the lower micrometer scale. Errors on this order of magnitude especially affect form and position deviations. Dimension-deviations can be recorded on replicas without significant deviations to the original value. The differences are typically smaller than 0.5% for lengths greater than 1 mm. Accordingly angles between different planes can also be recorded on replicas without significant deviation.

Table 4. Type 2 Objects – measurement results for the form, position and dimension deviations.

Flatness (Form)

Object	Original	Replica	Difference	
Plane 1...4	18.8 µm	26.0 µm	7.2 µm	38.1 %
Plane 5	4.2 µm	9.7 µm	5.5 µm	130.2 %

Parallelism (Position)

Object	Original	Replica	Difference	
P1/P3 P2/P4	61.2 µm	76.0 µm	14.9 µm	24.3 %

Plane Distance (Dimension)

Object	Original	Replica	Difference	
P1/P3 P2/P4	12.721 mm	12.693 mm	0.028 mm	0.221 %

Roundness (Form)

Object	Original	Replica	Difference	
Circle 1,2,3	10.0 µm	21.1 µm	11.1 µm	111.3 %

Hole Diameter (Dimension)

Object	Original	Replica	Difference	
Circle 1,2,3	5.200 mm	5.192 mm	0.008 mm	0.149 %

Angle (Dimension)

Object	Original	Replica	Difference	
P1...4 to P5	90.307 °	90.191 °	0.116 °	0.128 %
P1/P2 P3/P4	80.086 °	80.036 °	0.049 °	0.062 %

5. Conclusion

This study has introduced the IWF-Wunder method to preserve geometrical features of tools and workpieces. The method allows location- and time-independent quality control of tools and workpieces in research and development. The method enables frequent quality control checks during machining processes as well as a more efficient research.

5.1. Roughness Measurement

The IWF-Wunder method is suitable for analyzing machined surfaces with surfaces roughnesses greater than or equal to $R_a = 0.1\ \mu$m. Differences less than 10% of the R_a-value between original and replica can be achieved in general. Careful sample preparation is prerequisite. R_z-values can also be measured in the range greater than $R_a = 0.1\ \mu$m. Measurements on areas including obvious replication errors should be avoided. For surface roughnesses $R_a < 0.1\ \mu$m the method is not suitable in general. Especially the polyvinyl siloxane material for the imprints would require a lower viscosity. A lower viscosity would reduce the applicability, e.g. the measurement of vertical surfaces would be impossible. Nevertheless applications and processes generating very smooth surfaces and small geometrical features such as ultra-precision grinding, micromachining and MEMS-products are advancing [27-29]. An adapted replication process with materials of low viscosity would be required. During the evaluation the smallest difference between original and replica is measured using white light interferometer. Tactile measurement provides almost equally good result quality as the WLI. The tactile measuring-process is fast and independent from optical surface properties on the replica. In general, tactile measurement is recommended.

5.2. Form, Position and Dimension Measurements

The IWF-Wunder method has proven to be a well applicable tool for dimensional measurements of replicas. The accuracy is sufficient for applications with dimensions greater than 1 mm. Tool and workpiece features can be controlled using the technology. In contrast, the suitability of the IWF-Wunder method for form and position measurements is not given. The accuracy of the positive replica is insufficient for research and development. In [1] the potential on wear investigation has already been demonstrated.

5.3. General Statement

Careful sample preparation and replication allows accuracy comparable with the presented study. Nevertheless the accuracy depends on the user, application technique, measurement devices, and the original part. For higher quality requirements, pretesting is recommended.

Local errors forced by the replication process (e.g. during imprinting, epoxy casting) cannot be excluded. Thus it is recommended to obtain data from more than one measurement area. Measuring on areas with the above-mentioned errors reduces the result quality. Dataset with obvious replication errors should be disregarded.

References:

[1] S. Wunder, "Verschleissverhalten von Diamantabrichtrollen beim Abrichten von Korund-Schleifscheiben," DISS.ETH Nr. 20572, ETH Zürich, pp. 92-102, 2012.

[2] F. W. Pinto, G. E. Vargas, and K. Wegener, "Simulation for optimizing grain pattern on engineered grinding tools," CIRP Annals-Manufacturing Technology, Vol.57, No.1, pp. 353-356, 2008.

[3] J. C. Aurich, P. Herzenstiel, H. Sudermann, and T. Magg, "High-performance dry grinding using a grinding wheel with a defined grain pattern," CIRP Annals-Manufacturing Technology, Vol.57, No.1, pp. 357-362, 2008.

[4] H. N. Hansen, R. Hocken, and G. Tosello, "Replication of micro and nano surface geometries," CIRP Annals – Manufacturing Technology, Vol.60, pp. 5-20, 2011.

[5] H. N. Hansen and U. -A. Theilade, "Surface Microstructure Replication in Injection Moulding," Proceedings of the 1st International Conference on Multi-Material Micro Manufacture, Vol.4M, pp. 91-94, 2005.

[6] X. Han and H. Yokoi, "Visualization Analysis of the Filling Behaviour of Melt into Microscale V-Grooves During the Filling Stage of Injection Molding," Polymer Engineering and Science, Vol.46, No.11, pp. 1590-1597, 2006.

[7] G. C. Firestone and A. -Y. Yi, "Precision Compression Molding of Glass Microlenses and Microlens Arrays – An Experimental Study," Applied Optics, Vol.44, No.29, pp. 6115-6122, 2005.

[8] A. -Y. Yi, Y. Chen, F. Klocke, G. Pongs, A. Demmer, D. Grewell, and A. Benatar, "A High Volume Precision Compression Molding Process of Glass Diffractive Optics by Use of a Micromachined Fused Silica Wafer Mold and Low T_g Optical Glass," Micromechanics and Microengineering, Vol.16, pp. 2000-2005, 2006.

[9] J. Campbell, "Casting, Butterworths," London, 1993.

[10] J. A. Taylor, G. B. Schafer, and D. H. StJohn, "The Role of Iron in the Formation of Porosity in Al-Si-Cu-Based Casting Alloys: Part I. Initial Experimental Observations, Metallurgical and Materials Transactions A, Vol.30, Iss.6, pp. 1643-1650, June 1999.

[11] Y. Zhang, J. -C. Reed, and S. Yang, "Creating a Library of Complex Metallic Nanostructures via Harnessing Pattern Transformation of a Single PDMS Membrane," Journal of American Chemical Society, Vol.3, No.8, pp. 2412-2418, 2009.

[12] R. S. Scott, P. S. Ungar, T. S. Bergstrom, C. A. Brown, B. Childs, M. F. Teaford, and A. Walker, "Dental Microwear Texture Analysis: technical considerations," Journal of Human Evolution, Vol.51, pp. 339-349, 2006.

[13] Struers A/S. Repliset, "An advanced replica technique for the inspection of critical surfaces," www.struers.com [accessed July 23, 2013]

[14] Coltene Whaledent, Accu Trans, http://www.coltene.com/ [accessed July 23, 2013]

[15] J. -P. Butin, "Non Destructive Test by the Replica Method," Non-Destructive Methods, Vol.3, pp. 173-176, 1970.

[16] L. L. Nee, "Non-destructive Replica Metallography," British Journal of Non-Destructive Testing Vol.31, Iss.8, pp. 437-439, 1989.

[17] R. Wu, "Microstructural Study of Sanded and Polished Wood by Replication," Wood Science and Technology, Vol.32, pp. 247-260, 1998.

[18] W. Chee and T. Donovan, "Polyvinyl siloxane impression materials: A review of properties and techniques," The Journal of Prosthetic Dentistry, Vol.68, Iss.5, pp. 728-732, November 1992.

[19] V. Mazzarello, M. Cametti, G. Leone, P. Iacovelli, P. Ena, and G. Leigheb, "Analysis of the Microtopography of the Skin by Silicone Replicas after Repeated Exposure to Actinic Radiation at High Altitudes," Journal of the European Academy of Dermatology and Venereology, Vol.15, pp. 224-228, 2001.

[20] F. Klocke, A. Klink, and M. Henerichs, "ELID dressing behaviour of fine grained bronze bonded diamond grinding wheels," Int. J. Abrasive Technology, Vol.2, No.4, pp. 359-367, November 2009.

[21] H. Ohmori and T. Nakagawa, "Analysis of mirror surface generation of hard and brittle materials by ELID (electrolytic in-process dressing) – grinding with superfine grain metallic bond wheels," Annals of the CIRP, Vol.44, No.1, pp. 287-290, 1995.

[22] H. Ohmori, M. Mizutani, T. Kaneeda, N. Abe, Y. Okada, S. Moriyama, N. Hisamori, N. Nishimura, Y. Tsunashima, J. Tanaka, K. Kuramoto, and A. Ezura, "Surface generating process of artificial hip joints with hyper-hemispherical shape having higher smoothness and biocompatibility," CIRP Annals – Manufacturing Technology, Vol.62, Iss.1, pp. 579-582, 2013.

[23] H. Ohmori, W. Lin, Y. Uehara, Y. Watanabe, S. Morita, T. Suzuki, and K. Katahira, "Nanoprecision Micromechanical Fabrication," International Journal of Automation Technology, Vol.2, No.1, 2008.

[24] Alicona, "Infinite Focus for form and roughness measurement," http://www.alicona.com/home/products/infinitefocus-standard.html [accessed July 31, 2013]

[25] Zygo, "NewView^{TM} 7300 3D Optical Surface Profiler," http://www.zygo.com/?/met/profilers/newview7000/ [accessed July 31, 2013]

[26] G. Tosello, F. Marinello, and H. N. Hansen, "Characterization and Analysis of Micro Channels and Sub-Micron Surface Roughness of Injection Moulded Microfluidic Systems Using Optical Metrology," Polymer Process Engineering '09 Conference (PPE'09), Bradford, United Kingdom, Vol.27-28, pp. 199-232. October 2009.

[27] H. Ohmori, Y. Uehara, and K. Katahira, "Fabrication of Ultrafine Tools Using a Desktop Microgrinder," International Journal of Automation Technology, Vol.4, No.2, 2010.

[28] I. Ogura and Y. Okazaki, "Development of Micro Probe System for Micro Measurement Center," International Journal of Automation Technology, Vol.3, No.4, 2009.

[29] K.-C. Fan, K. Zhang, Y.-L. Zhang, and Q. Zhang, "Development of a Non-Contact Focusing Probe for the Measurement of Micro Cavities," International Journal of Automation Technology, Vol.7, No.2, 2013.

Name:
Marcel Henerichs

Affiliation:
Research Assistant, Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology Zurich (ETH)

Address:
Tannenstrasse 3, 8092 Zürich, Switzerland

Brief Biographical History:
2008 Visiting Scientist at RIKEN in Wako-shi, Japan
2008- Research Assistant at the ETH Zurich

Main Works:
• F. Klocke, A. Klink, and M. Henerichs, "ELID dressing behaviour of fine grained bronze bonded diamond grinding wheels," Int. J. Abrasive Technology, Vol.2, No.4, pp. 359-367, November 2009.
• C. Dold, M. Henerichs, L. Bochmann, and K. Wegener, "Comparison of ground and laser machined polycrystalline diamond (PCD) tools in cutting carbon fiber reinforced plastics (CFRP) for aircraft structures," CIRP Procedia, Vol.1, pp. 178-183, 2012.
• C. Dold, M. Henerichs, P. Gilgen, and K. Wegener, "Laser Processing of Coarse Grain Polycrystalline Diamond (PCD) Cutting Tool Inserts using Picosecond Laser Pulses," Physics Procedia, 2013, Vol.41, pp. 603-609.

Name:
Michael Egeter

Affiliation:
Student M.Sc., Mechanical Engineering, Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology Zurich (ETH)

Address:
Tannenstrasse 3, 8092 Zürich, Switzerland

Membership in Academic Societies:
• Swiss Engineering (STV)
• European Society for Precision Engineering and Nanotechnology

Name:
Thomas Liebrich

Affiliation:
Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology Zurich (ETH)

Address:
Tannenstrasse 3, 8092 Zürich, Switzerland

Brief Biographical History:
2006 M.Sc. in Mechanical Engineering at ETH Zurich
2012 Ph.D. in Mechanical Engineering at ETH Zurich
2006-2013 Research Assistant at IWF/ETH Zurich

Main Works:
• "3D-probing system for micro-components", Fortschritt-Berichte VDI, Reihe 8, Nr.1212, VDI Verlag, ISBN: 978-3-18-521208-6, 2012.
• "Improvements and experimental validation of a 3D-probing system for micro-components," CIRP Annals – Manufacturing Technology, Vol.61, No.1, pp. 475-478, 2012.
• "Calibration of a 3D-ball plate," Precision Engineering, Vol.33, Iss.1, pp. 1-6, January 2009.

Membership in Academic Societies:
• European Society for Precision Engineering and Nanotechnology

Name:
Robert Voß

Affiliation:
Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology Zurich (ETH)

Address:
Tannenstrasse 3, 8092 Zürich, Switzerland

Brief Biographical History:
2013- Starting Ph.D. at ETH Zürich, Institute for Machine Tools and Manufacturing

Name:
Konrad Wegener

Affiliation:
Institute of Machine Tools and Manufacturing (IWF), Swiss Federal Institute of Technology Zurich (ETH)

Address:
Tannenstrasse 3, 8092 Zürich, Switzerland

Brief Biographical History:
1990 Ph.D. at TU Braunschweig
1990-1999 Head of Design and Layout planning Departements at Schuler Presses GmbH
1999-2003 CTO of Schuler Laser
2003-present Head of Institute of Machine Tools and Manufacturing

Main Works:
• E. Weingärtner, K. Wegener, F. Kuster, "Wire electrical discharge machining applied to high-speed rotating workpieces," Journal of Materials Processing Technology, ISSN 0924-0136, DOI 10.1016/j.jmatprotec.2012.01.005, Band 212, Nr.6, pp. 1298-1304, 2012.
• M. Ess, J. Mayr, S. Weikert, and K. Wegener, "Thermal Model of Machine Tool Feed Drivetrains," American Society for Precision Engineering, Denver, USA, November 13-18 2011, ISBN 978-1-887706-58-2, Vol.52, pp. 292-302, 2011.
• K. Wegener, C. Dold, M. Henerichs, and C. Walter, "Laser prepared cutting tools," Laser Assisted Netshape Engineering / Physics Procedia, 2012, Fürth, Deutschland, ISSN 1875-3892, DOI 10.1016/j.phpro.2012.10.035, Band 39, pp. 240-248.
• N. Rüttimann, S. Buhl, and K. Wegener, "Simulation of Single Grain Cutting Using SPH Method," Journal of Machine Engineering, Polen, Band 10, Nr. 3, pp. 17-29, 2011.

Membership in Academic Societies:
• The International Academy of Production Engineering (CIRP)
• Gesellschaft für Angewandte Mathematik und Mechanik (GAMM)