DOI: 10.7795/810.20180323D

Traceable measurements of rounded cutting tool edges

Anaïs Nicolet and Felix Meli*

Federal Institute of Metrology METAS, Lindenweg 50, 3003 Bern-Wabern, Switzerland

** Corresponding author: felix.meli@metas.ch*

Keywords: edge radius, asymmetric edges, cutting tools, micro contour

Abstract

The edge geometry of a cutting tool is of extreme importance for its performance and thus of great interest to the machine tool industry. The sharp cutting edges are processed to obtain specific edge roundings. Commercially available optical edge shape measuring instruments require suitable calibrated edge artefacts in order to achieve traceability.

This study uses a specially adapted tactile profiler measurement method and a tailored evaluation program for the calibration of various cutting tool edge shapes. For the evaluation, parameterized mathematical models of the ideal edge shape are formulated. The model parameters are then determined by least squares curve fitting over the entire edge zone. Using simulations, this method has proven to be robust for symmetric and asymmetric edges even if large form deviations are present.

1 Introduction

The process of stock removal with cutting tools is very important for the machine tool industry and many details have been studies so far [1, 2, 3]. For long tool lives, the cutting tools are made of hard materials, mostly tungsten carbides, and are often additionally coated with even harder materials such as nitrides or diamond. In recent years, the tool edge shape has been optimized [4, 5] and corresponding commercial measurement instruments and analysis procedures were developed [6, 7, 8, 9, 10].

The initially sharp cutting edge is processed in an additional production step to obtain a specific edge geometry as for example rounded symmetric or asymmetric edges or various combinations of chamfers (fig. 1). It has been shown that edge radii in the range of a few micrometres up to about 60 µm increase the tool life time and allow higher cutting speeds by avoiding chipping of the tool edge [11]. Shaping a tool edge can be performed with methods such as sandblasting, barrel finishing (also known as trowalizing), vibratory grinding, etching or brush sanding also named flakkoting [4, 12, 13].

The wear of cutting tools is measured optically and if possible in the production line in order to increase the efficiency. Instruments for edge measurements are typically 3D optical microscopes, because optical measurements are fast, but also stylus profilers can be applied. The commercially available dedicated optical instruments are often based on focus variation, confocal microscopy or fringe projection [8, 10]. Optical measurements provide high resolution in the direction of the light propagation but are limited in lateral resolution due to diffraction effects. Furthermore, additional unwanted artefacts may arise from the surface state. The accuracy of these measuring methods should be validated using calibrated reference artefacts. Traceable reference measurement methods are required for the calibration of the artefacts.

Of major concern are also robust and user independent data evaluation methods which perform well even in the case of high form deviations, a situation which is rather often observed for tool edges. For example, when working on an instrument using the focus variation principle a certain surface roughness is even necessary, to obtain good results. The high roughness induces nevertheless form deviation on the edge shape.

A previous comparison has revealed considerable discrepancies among different edge evaluation methods [14]. Specially adapted tactile profiler measurements can provide traceability and tailored evaluation programs robust and user independent data evaluation. The following sections will present and discuss the measurement method and the evaluation program developed at METAS for traceable measurements of rounded edges.

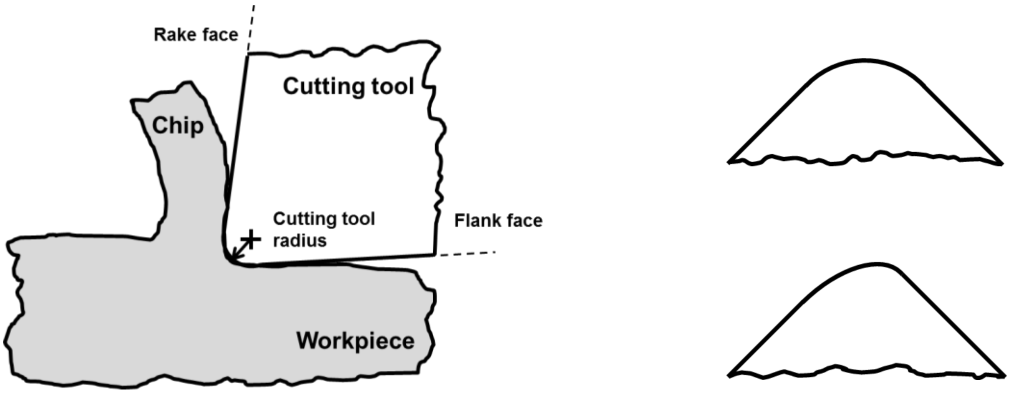

Figure 1 Left: workpiece and cutting tool with indicated cutting edge radius. Right: idealized symmetric (top) and asymmetric (bottom) edge roundings.

2 Traceable tactile profiler measurements

Tactile edge measurements were performed using a commercial surface profiler (MarSurf LD130) with a stylus having a spherical probe tip on a conical shaft. Profile data are acquired at a very low scan speed of 0.1 mm/s with a point density of 10’000 points/mm. Several profiles are usually acquired orthogonal to the edge. This procedure can also be applied in the case of curved edges. The spherical probe tip requires an accurate radius calibration and a corresponding profile correction. Special attention is payed to the resulting slope and curvature dependent probing point density which can lead to unwanted weighting of profile segments during the fit procedure if left uncorrected These considerations are explained in detail below.

2.1 Probe stylus

As the spherical stylus tip scans over the edge artefact, its dimension and form have an important influence on the measurement result. Both the stylus radius and its form deviation have to be known as precisely as possible. The used spherical stylus tip, consisting of a ruby sphere, was thus calibrated using the METAS micro coordinate measuring machine (µ-CMM) [15]. The sphere radius of 150 µm was measured with an uncertainty of 50 nm and the measured form deviation is well below 150 nm.
While the probe scans over the edge, the contact angle changes during the scan and therefore also the contact force direction changes. This can induce variable bending of the probe shaft (fig. 2 left), which influences the final result. A 60° conical stylus shaft with the calibrated spherical probe directly at its end was specially developed for this kind of measurement. Unwanted bending effects, which were originally observed on a standard stylus, could thus be avoided (fig. 2 right).

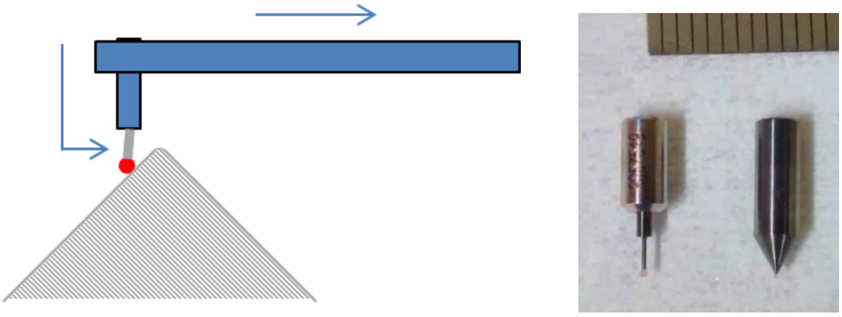

Figure 2 Left: illustration of probe shaft bending. Right: weak stylus with thin cylindrical probe shaft and rigid stylus with special robust conical shaft. The diameters of the ruby spheres shown are 0.5 mm for the stylus on the left and 0.3 mm for the one on the right.

The precision of an edge curvature evaluation is influenced by the scaling and orthogonality of the x-axis and z-axis of the profiler. After calibration of the stylus arm geometry on a calibrated reference sphere, two verification measurements are performed on independently calibrated artefacts to verify the accurate axes calibration. The first artefact is a glass fibre (ø 125 µm), beforehand calibrated on the METAS µ-CMM [15], and the second artefact is a diamond knife edge used for slice preparation in histology from Diatome AG (r < 5 nm), calibrated on the METAS metrology AFM [16]. The corresponding surface profiler measurements are used for small corrections and validation.

Due to the spherical shape of the tip, the raw measured profile over the edge is a convolution of the edge shape and of the probe shape (fig. 3). At each measured point, the radius of the ruby probe needs to be subtracted, orthogonally to the measured profile. The orthogonal direction is obtained using two different methods:

1. Local slope: the local slope is calculated from a fixed number of measured points around the considered point. The orthogonal direction is the negated inverse of the slope value.
2. Fit: the measured profile can be described by a mathematical function, whose parameters are obtained by a least-square fit on the data points. From the obtained model parameters it is then possible to determine the normal direction of the profile.

The second method can only be applied in the case of symmetrical edges, because then the edge shape can be described mathematically as a combination of two straight lines linked by a circular arc (fig. 6 left). In the case of the ellipse, method 1 from above is used, as the measured profile cannot easily be described by a mathematical function: the convolution of an ellipse and a circle is neither a circle nor an ellipse.

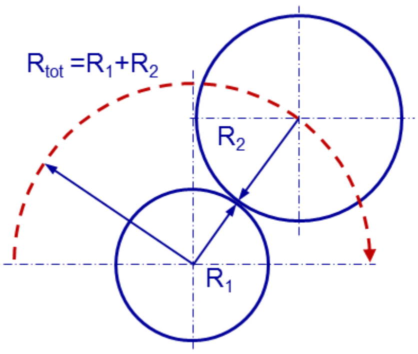

Figure 3 Convolution of the edge shape with the tip shape.

2.2 *Point density, rotation, range and resampling*

Once the profile is probe corrected with one of the methods from above, the point density along the x-axis has changed, because of slope variations. Especially on the rounded edge, the point density has now significantly increased (fig. 4). To avoid unequal weighting of different profile regions in the fitting procedure, the point distances have to be adjusted to the same value along the whole profile.

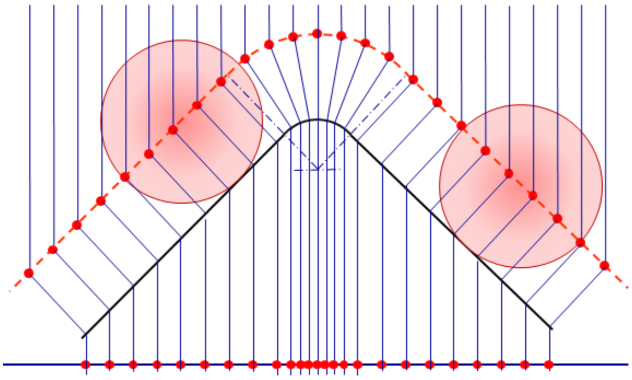

Figure 4 Evolution of the point density before and after the probe correction.

Before the profile point resampling is made, the tip corrected profile is rotated to the final optimal orientation, so that the bisector of the wedge angle is parallel to the z-axis. To perform the orientation procedure independent of an operator a first coarse fit is made automatically. This fit is only used to find the initial profile orientation.

Next the profile is clipped to the desired evaluation range. The remaining points in the clipped profile are then regularly redistributed to achieve an equal point density along the edge profile.

The selection of the radius evaluation range of an ideal edge is uncritical (fig. 5 left). However due to form deviation and/or roughness observed on real profiles (fig. 5 right) a manual selection of the evaluation range may become ambiguous. A robust selection of the evaluation range can be achieved by the method presented in the following chapter where the entire edge zone, including the edge flanks, is selected as the evaluation range.

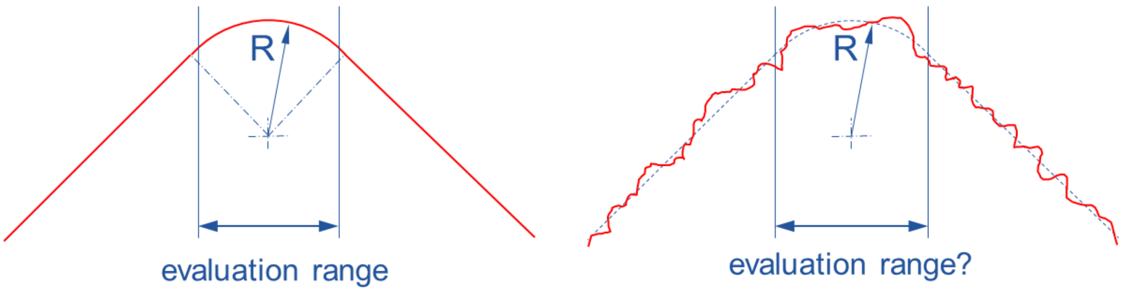

Figure 5 Uncritical selection of the radius evaluation range on a perfect profile (left) and ambiguous evaluation range in case of a realistic profile having considerable form deviation (right).

3 Edge shapes

3.1 Selected edge models

For the edge shape evaluation, parameterized mathematical models of the ideal edge shapes are formulated. The model parameter values and the deviation from the model are then determined by least squares curve fitted over the entire edge evaluation range.

Initially, a model for the evaluation of circular rounded symmetric tool edges was developed. It consists of two straight lines linked by a circular arc (fig. 6 left). This model was now expanded to characterize also asymmetric edges (fig. 6 middle and right), called waterfall or trumpet edges. For these asymmetric edges an elliptical arc substitutes the circular arc.

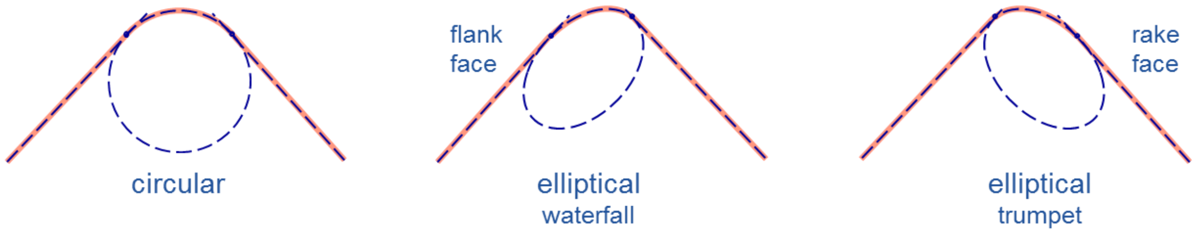

Figure 6 Illustration of possible symmetric and asymmetric edge shape models.

3.2 Numerical implementation

Tailored evaluation programs were developed for symmetric and asymmetric edges. The used mathematical edge description is a parameterized mathematical model of the ideal edge shape having tangential transitions between the straight lines and the circle/ellipse. The type of the designed edge shape geometry has to be known in advance in order to select the appropriate fitting model. The wedge angle, the transition points, the centre of the circle/ellipse and the radius of the circle, respectively the semi major axis and semi minor axis of the ellipse (fig. 7) are fit determined model parameters. Additionally, from the model parameters, the length ratio of the straight lines, from the tangential transition point of each edge face, up to the crossing point ($S\gamma$ and $S\alpha$, in figure 7 right), serves as a measure for the edge asymmetry (K-factor: $S\gamma/S\alpha$). Of course, the type of the designed edge shape geometry has to be known in advance in order to select the appropriate fitting model.

A least-square Levenberg-Marquardt fit is used to optimize the edge model parameters: the sum of the squared differences between the measured points and the fit is minimized. For each point the measured difference is along the z-axis and is thus not orthogonal to the measured profile. This has a weighting consequence: the steeper the local slope, the larger is the difference between a measured point and a point from the fit. To get over this problem, the measured points are inversely weighted based on the absolute value of the local slope: the higher the slope, the smaller the weight on this point.

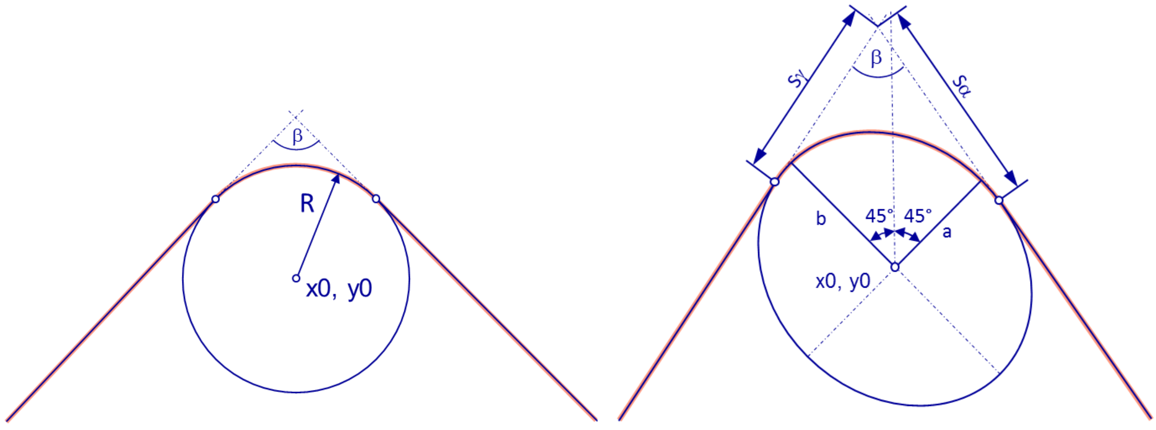

Figure 7 Developed symmetric (left) and asymmetric (right) models for the evaluation of rounded edges with indication of the corresponding model parameters. β: wedge angle, R: circle radius, (x0, y0): center coordinates of the circle or the ellipse, (a, b): semi-minor and semi-major axis of the ellipse, $\kappa = S\gamma/S\alpha$: asymmetry factor.

For edges having flank lines that are not perfectly straight, the selected evaluation range has also a small influence on the final estimated fit parameters. The longer the evaluation range is with respect to the radius value, the more influence or weight is given to the flanks. In the software it is possible to choose the evaluation range as a defined x-range, a defined z-range or as a multiple of the radius. A convenient recommendation is to use approximately 10 times the nominal radius value as whole evaluation range (in the x-direction) [14]. However as these edge reference artefacts are often used with optical microscopes, it is important that the evaluation range can be covered by the selected objective so that both, the calibration and the measurement, agree.

3.3 Numerical edge simulations

The evaluation software and its algorithm were tested using simulated profiles. To the ideal edge shape, low frequency (resembling form deviation) and high frequency (resembling roughness) noise was added (fig. 8). If high frequency noise is added with 1.5 µm amplitude on a 20 µm radius, the standard deviation of the resulting radius values is about 1%. In the case of low frequency noise with the same amplitude, the standard deviation rises to 6%.

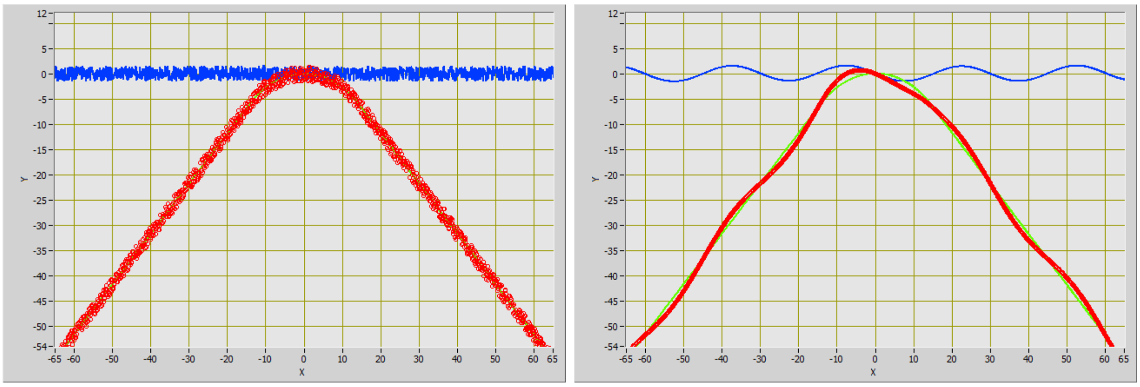

Figure 8 Profile simulations with high frequency noise (left) and low frequency undulation distortions (right). R= 20 µm, distortion amplitude 1.5 µm (red: simulated profile, green: fit, blue form deviation).

4 Measurement example

With the edge simulations, the models have proven to be reliable and are now in use for calibration services. Figure 9 shows a typical profile deviation of a measured edge with a 20 µm radius, fitted with both the symmetric and the asymmetric model.

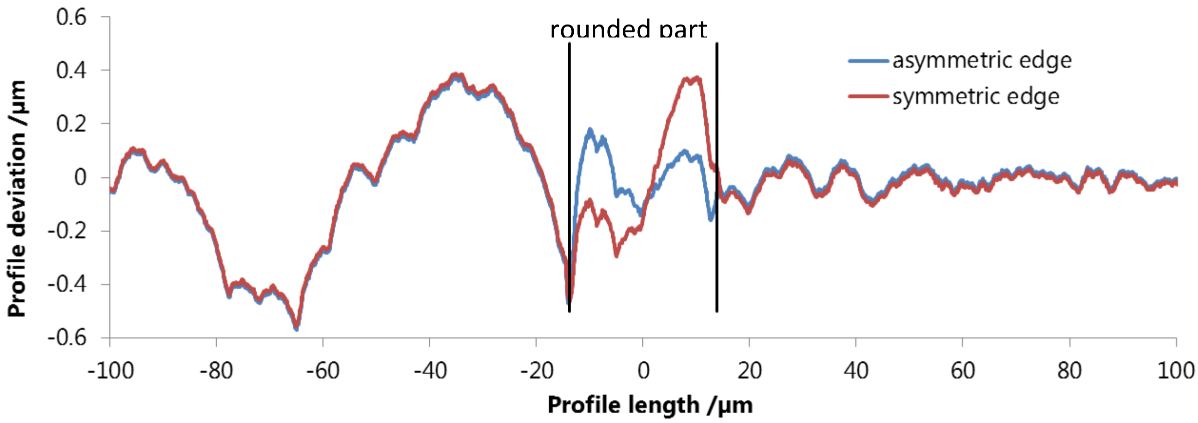

Figure 9 Profile deviations for the symmetric (red) and asymmetric (blue) model when applied to a measured edge profile with a nominal radius of 20 µm.

Along the flanks, a rather large form deviation is observed. Also the form deviations on the left flank are very different from those seen on the right flank. This observation can be explained by different shaping processes applied to the two sides. Within the rounded edge section, the profile deviation is smaller for the asymmetric model fit. This is an expected behaviour as there is one additional parameter to describe the edge in the asymmetric model.

5 Uncertainty evaluation

The uncertainty of the radius was determined using an empirical model. Four main components contribute to the uncertainty: the repeatability, the straightness of the profiler guide, the deviations observed on the METAS validation artefacts and the measured form deviation of the edge.

The repeatability contribution includes the repeatability of the instrument and the variability of the edge, as always several profiles are acquired. The straightness term is the deviation of the profiler guiding system within the used measurement range. The uncertainty contribution estimated using the METAS validation artefacts (glass fibre and diamond knife) is a combination of the form and the diameter deviation of the reference sphere used for the calibration of the stylus arm and of possible remaining stylus arm instabilities. A fraction of the measured form deviation of the edge is used as the last contribution to cover some method definition dependent contributions. If the selected evaluation range is considered as a method defined parameter, then the uncertainty contribution due to the form deviation would not be necessary. However, as there is so far no standardised measurement procedure, different measurements methods can equally be applied and therefore a contribution dependent on the form deviation of the edge was added. For a perfect edge the contribution would be negligible but for the typically observed edge shape deviations this can have a significant influence.

While the uncertainties due to the profiler straightness and due to the reference artefact deviations are instrument dependent, the uncertainties due to the edge uniformity and due to the observed form deviation are artefact dependent. In table 1 a typical example of an uncertainty budget for the radius parameter with the importance of the different contributions is given.

Table 1 An empirical measurement uncertainty model with 4 major contributions is used for each of the fitted model parameters. Below the estimation for the radius value is shown.

Description	**Quantity**	**Unc.**	**[U]**	**Distribution**	**ν**	**Sens. coeff.**	**Std.Unc./µm**
Edge uniformity & repeatability	*Std R*	0.4	µm	1	8	1	0.14
Profiler guide straightness	*Str*	0.02	µm	1	20	1	0.02
Reference artefacts	*Cal*	0.28	µm	1.73	20	1	0.16
Form deviation	*F*	0.6	µm	1	20	0.1	0.06
						Standard Uncertainty	0.22
						ν_{eff}	30
						$k_{95\%}$	2.05
						expanded Uncertainty (U_{95})	**0.45**

6 Conclusion and outlook

A new calibration service was developed for symmetric and asymmetric cutting edge reference artefacts. Because of their importance in the machine tool industry, a traceable calibration of the edge shape is of great interest. The new service allows the calibration of symmetrically or asymmetrically rounded edges. The influence of various factors was investigated, such as the profiler calibration, the stylus probe properties, the data point density, the fitting, the evaluation range, etc.

The current models with tangential transitions, could be expanded by additional models having for example rounded edges without tangential transitions or edges with one or multiple chamfers. The difficulty in the model expansion lies in the practical realisation of suitable artefacts. In future, we hope that accurate edge shape measurements will help to improve the cutting tool performance even further.

References

[1] Denkena, B., Becker, J. C., & de Leon-Garcia, L. (2005, May). Study of the influence of the cutting edge microgeometry on the cutting forces and wear behaviour in turning operations. In *Proceedings of the 8th CIRP, International Workshop on Modelling of Machining Operations, Chemnitz, Germany* (pp. 503-507).

[2] Tikal, F. (Ed.). (2009). Schneidkantenpräparation: Ziele, Verfahren und Messmethoden: Berichte aus Industrie und Forschung. Kassel University Press GmbH.

[3] Leidich, E., Bruzek, B., (2012 March). Einfluss von Radien und Fasen auf die Festigkeitsberechnung, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 32-39.

[4] Thiel, W., (2012, March). Reproduzierbare Verrundung von Schneidkanten an Mikrowerkzeugen, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 63-70.

[5] Lümkemann, A., Müchel, C., Cselle, T., Morstein, M., (2012, March). Schneidkantenpräparation und Beschichtung: Schlüsselrollen beim Optimieren von Hochleistungswerkzeugen, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 71-78.

[6] Grübler, T., (2012 March). Anwendung der BOSCH-Norm zur Messung von Kantenbrüchen mit Hilfe von optischer Oberflächenmesstechnik, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 48-55.

[7] Zind, S., Dültgen, P., (2012 March). Kantenspezifikation durch Volumenelemente, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 79-86.

[8] Frankowski, G., (2012 March). Optische 3D-Messung von Kanten und Radien an Werkzeugen und Bauteilen, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 103-110.

[9] Christoph, R., Schmidt, I., (2012 March). Messung von Radius und Kantenbruch mit Multisensor-Koordinatenmesstechnik, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 149-165.

[10] Wiora, G., Grigat, M., Valentin, J., (2012 March). Konfokales Messsystem zur Geometrie- und Rauheitsmessung an Klingen und Schneidkanten, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 184-191.

[11] Smith, G. T., (2008). Cutting Tool Technology, Industrial Handbook, Springer, London. 10.1007/978-1-84800-205-0

[12] Lahmann, H.-W., Preiss, P., (2012 March). Schneidkantencharakterisierung – Anforderungen und Erfahrungen aus Sicht einer Werkzeugforschungseinrichtung, *XIII. Internationales Oberflächenkolloquium, 1. IMSAS-Treffen: Kanten und Radien*, Chemnitz, Germany, 87-94.

[13] http://profin.ch/en/home (last visit 23.11.2017)

[14] Felgner, A., Grabner, M., Helmli, F., Krüger-Sehm, R., Küng, A., Meli, F., (2012, March). Auswirkung verschiedener Auswertestrategien auf die Radiusmessung von Schneidkanten, *1. IMSAS-Treffen: Kanten und Radien, XIII. Internationales Oberflächenkolloquium*, Chemnitz, 174-183.

[15] Küng, A., Meli, F., Thalmann, R., (2007). Ultraprecision micro-CMM using a low force 3D touch probe, *Meas. Sci. Technol.* 18, 319–327.

[16] Meli, F., Thalmann, R. (1998). Long-range AFM profiler used for accurate pitch measurements *Meas. Sci. Technol*. 9 1087–92.