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Influence of cutting edge radius on cutting forces in machining titanium

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ABSTRACT

The performance of machining titanium can be enhanced by using cutting tools with rounded cutting edges. In order to better understand the influence of rounded cutting edges and to improve the modelling of the machining process, their impact on active force components including ploughing forces and tool face friction is analysed. This paper presents experimental results of orthogonal turning tests conducted on Ti–6Al–4V with different cutting edge radii and changing cutting speeds and feeds. As an accurate characterisation method for the determination of the cutting edge radius is prerequisite for this analysis, a new algorithm is described which reduces uncertainties of existing methods.

1. Introduction and motivation

Titanium is classified as a difficult-to-machine material. Its mechanical and chemical properties cause high wear on cutting edges. By preparing cutting edges with defined roundings, initial crack formation can be reduced, the mechanical strength of a cutting edge can be improved and the load on the cutting edge is changed. Different researchers proof an enhanced tool life when using cutting tools with rounded cutting edges [1–3]. The optimum cutting edge radius for a machining process depends on the work material, tool material and machining conditions. To better understand the relation between cutting edge radius, tool wear and forces acting on the cutting edge itself, it is necessary to run experiments in which this load is determined.

Generally, total forces recorded in a cutting process are the sum of forces acting on the tool flank and its cutting edge, as well as on the face. The force acting directly on the cutting edge, is called ploughing force F_{Pl}, see Fig. 1. It originates from elastic and plastic deformation of the work material around the cutting edge. The ploughing force is also referred to as parasitic force or zero-feed force [4–6]. In literature, different methodologies exist to reveal the ploughing force [4,5]. Its determination and separation from the total forces allows a better understanding of tool wear and shearing process, and enables the determination of actual coefficients of friction in a cutting process. For the machining of titanium no information about the contribution of the cutting edge radius on ploughing forces is available.

This paper presents experiments, in which the influences of the rounded cutting edge radius r_n and cutting speed v_c on the total force and ploughing force in machining titanium alloy Ti–6Al–4V is analysed. As essential precondition, such analysis needs a precise cutting edge preparation and characterisation method featuring high repeatability. Currently available characterisation methods for rounded cutting edges are found to be not repeatable. A recent survey [7] compares the cutting edge radius measurement of different institutions. It shows significant deviations in the determined radii. The non-standardised characterisation algorithm is seen as one cause for the detected discrepancies. Therefore, a new characterisation algorithm was necessary to be developed which reduces uncertainties of existing methods. This in turn enables a higher accuracy in determining the influence of the cutting edge radius on ploughing forces.

2. Characterisation of rounded cutting edges

No international standard yet exists that defines how the micro geometry of a cutting edge profile has to be described. The characterisation of a rounded cutting edge by its radius is mentioned in *DIN 6582* [8]. Unfortunately, no details are given about how the area for a circle fitting is to be chosen or what fitting procedure is to be used. This missing detail is a major drawback in the application of this method. Thus, results may differ depending on measurement uncertainty, user, fitting area and procedure used for the fitting. Other attempts for the characterisation of rounded

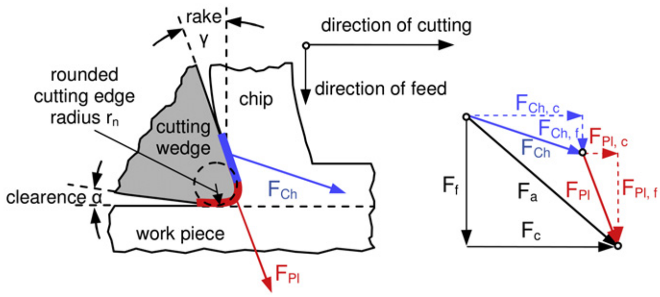

Fig. 1. Separation of active force F_a into ploughing force F_{Pl} and chip forming force F_{Ch} and into components in feed and cutting direction, after [4].

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cutting edges [9,10] exist. However, in some cases their significance and applicability is strongly influenced by the uncertainty factors mentioned, too, and the same characterisation method may produce different results for the characterisation of a cutting edge.

In general, the uncertainty of a circle fitting depends on the point uncertainty, the number of points and the area chosen for the fitting. To reduce uncertainties in the characterisation an algorithm was developed that defines its fitting area iteratively as a function of edge flattening and wedge angle β of the cutting edge. By making the fitting area user independent, the repeatability increases. As one uncertainty driver – definition of cutting area – is eliminated, the resulting characterisation uncertainty is reduced. The mathematical determination of the fitting area is accomplished proposing the following algorithm. The steps described are illustrated in Fig. 2 with the number indicated.

(1) A least squares straight line fitting is accomplished on flank and face over an area preset to a certain distance to the nose tip. An eligible value for the distance corresponds to the maximum of the cutting edge rounding expected. In this example a value of 200 μm is chosen. If a nonrealistic value is chosen, e.g. 0 μm or several mm, the error will be compensated within the next iterative steps. The fitting length should be chosen in such a way that a macro geometrical curvature of flank and face is not causing an inappropriate fit and still represents the effective working geometry. Thus, the considered length should correspond with the maximum uncut chip thickness the tool is proposed to be used for. In this case a fitting length of 300 μm is chosen.
(2) The least squares fitted straight lines cross in point p_c. The angle inscribed by these straight lines is the wedge angle β. The wedge angle bisector gives as intersection with the cutting edge profile point p_{int}.
(3) Draw a circle that intersects point p_{int} and is tangent to both straight fitting lines. The points where the circle touches the fitting lines represent the new upper limit for the least squares straight line fitting of flank and face.
(4) Steps (2) and (3) are repeated until the distance between the points where the straight lines are tangent to the circle and the upper fitting limit of the foregoing step is approximating zero. These points are the limit finally representing the transition from macro to micro geometry.
(5) Generate a least squares reference circle using all points within the micro geometry limit. The circle does not necessarily need to touch the fitting lines nor is its centre necessarily on the wedge angle bisector. The radius r_n of the fitted circle represents the radius of the rounded cutting edge.

Following this algorithm a circle fitting is achieved that gives a unique solution for the characterisation of a rounded cutting edge by its radius r_n independent from starting values. To characterise the asymmetry of a rounding further parameters have to be used, e.g. distances between cutting edge profile and an auxiliary horizontal straight line left and right to the wedge angle bisector.

For an ideal radius of $r_n = 50$ μm, 100 evenly distributed measurement points over an angular range of $\alpha_r = 90^\circ$ and a measurement uncertainty for one point of $U = 0.5$ μm, the resulting radius uncertainty is 2% of the diameter, based on an uncertainty range of $P = 95\%$ ($k = 2$).

3. Experimental setup

Free orthogonal cutting tests on titanium (Ti–6Al–4V) were performed on a *Schaublin 42 LT M13* lathe. The work material was forged and annealed. The mechanical properties of the titanium used are listed in Table 1.

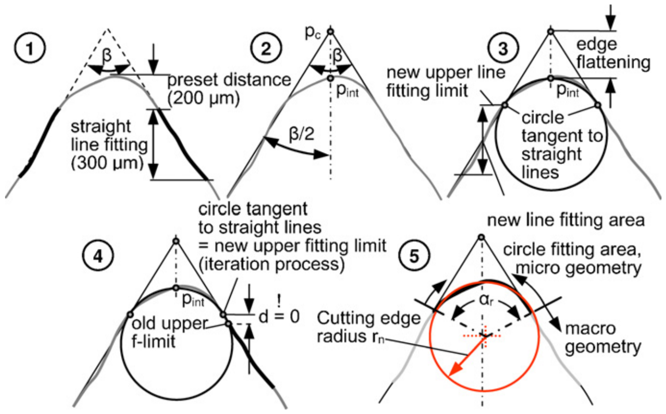

Fig. 2. Steps to characterise the rounding of a cutting edge profile by a Gaussian fitted circle with a unique solution.

Cutting forces F_c and feed forces F_f were measured using a *Kistler 9121* three-component force dynamometer. Oil was used as coolant, which was supplied via an external nozzle to the cutting process.

Indexable cutting inserts made of WC/Co with a medium grain size were used as cutting tools. The inserts were ground with a rake of $\gamma = 10^\circ$ and a clearance of $\alpha = 8^\circ$. The edges were symmetrically rounded with radii r_n between 10 ± 1 and 50 ± 1 μm. The cutting edge roundings were generated by micro-abrasive jet machining. The abrasive (Al_2O_3) was directed onto the cutting edge through a jet nozzle which was guided by an NC controlled six-axis-robot. The robot guided process enables a reproducible generation of constant roundings along a cutting edge. The radii were determined using the characterisation method described above. An *Alicona InfiniteFocus* device was used as measurement instrument.

In the experiments, the feed f and thus the uncut chip thickness t was varied between 0.01 and 0.2 mm. The cutting width was set to $b = 2$ mm. Cutting speed v_c was varied between 10, 30, 70 and 110 m/min. To avoid influences of tool wear, all tests were performed using new cutting edges.

4. Results

4.1. Influence of rounded cutting edge radius r_n on cutting force F_c, feed force F_f, ploughing force F_{Pl} and coefficient of friction μ

For different uncut chip thicknesses t, Fig. 3 represents the cutting forces F_c and feed forces F_f in orthogonal turning of Ti–6Al–4V using rounded cutting edges with different radii r_n. The force values are standardised to a cutting width of $b = 1$ mm. As can be seen, both force components increase when increasing the cutting edge radius. The cutting force is less sensitive to a change in cutting edge radius than the feed force. The influence of uncut chip thickness t is non-linear for small values of t. This is indicated by the dashed lines in Fig. 3. For larger values of uncut chip thickness the relation between forces and uncut chip thickness can be linearly approximated (full straight lines in Fig. 3).

For the determination of ploughing force components $F_{Pl,c}$ and $F_{Pl,f}$ from this data, the same approach as reported in [4] is used. The approach is based on the assumption that (1) the total force in a cutting process increases linearly with increasing feed, provided that the zone of the cutting edge, which is influenced by the ploughing force, is fully engaged; (2) the ploughing force F_{Pl} does

Table 1
Mechanical properties of Ti–6Al–4 V (forged and annealed).

Proof stress $R_{p0.2\%}$ (N/mm^2)	Proof stress $R_{p1\%}$ (N/mm^2)	Tensile strength R_m (N/mm^2)	Elongation A_4 (%)	Elongation A_5 (%)	Reduct. of area (%)
920	955	965	16	14	39