Simulation of geometrical influences of PVD hard coatings on the micro drills

E. Lugscheider, N. Papenfuß-Janzen , V. Hurevich

Material Science Institute RWTH University, Aachen

The presented article is concerned with the study of the geometrical influence of PVD deposited hard coatings on the drilling process. The drill twisting is considered, and a FEM model to simulate the contact between a drill and a billet to be drilled is developed. Some numerical investigations are carried out. A special attention is paid to the investigation of effects related to sizes scaling which are taking place at micro drilling only.

1 Introduction

Drilling represents one of the most widely used manufacturing processes and has significant economic importance. Industry imposes severe requirements upon the drilling process concerned the accuracy, the automation, high speed drilling and the possibility to drill difficult-to-cut materials. The modern economical and ecological requirements can be satisfied by a new dry treatment technology without any lubricant.

The above-called requirements lead to a frequent use of wear resistant coatings. The coating is deposited on the drill mainly by the PVD technology. Titanium nitride (TiN), titanium carbon nitride (TiCN), and diamante are used as coating materials [1]. The last one is characterised by fabrication difficulties and high prices. Titanium aluminium nitride (TiAlN) coating is applicable at high temperatures and can be used in dry drilling.

Micro-drilling is a drilling process with drill diameters down to 0.1 mm. Micro-drilling is widely used in printed circuit boards [2] and in medicine applications. Wear resistant coatings, deposited on a small drill, influence not only on local parameters like hardness, but also on global parameters, like flexural rigidity of the drill. Actually, the typical coating thickness obtained by PVD technology is about 5 μm, that reaches 5% of the drill diameter and can be comparable with the sizes of smaller drill details that causes geometrical modifications of the drill. A special importance has the curvature radius modification of the chisel edge, because it influences the critical loads required for cutting. This influence will be discussed more in details below.

The small drills are more at risk to be broken[3]. Resuming the investigation carried on by Shaw [4] shows, that the most likely cause of drills failure is breakage as result of too great a torque or a twist, playing a decisive role especially by drilling long holes. The main aim of the presented article is to develop theoretical models to carry on mechanical analysis of micro-drills taking into account the influence of the coating.

2 Twisting model

2.1 General considerations

The aim of the twisting investigation is to predict the deflections of the drill. The drill itself has a quietly complicate helical geometry with many different-oriented surfaces close to the chisel edge. The deflection of a point is interpreted as its displacement. Therefore, in order to study the deflection, it is required to fix a point and to compute its displacement. It is well known, that the most critical points (the points with the largest displacements) are situated on the surfaces. Moreover, from several previous studies [4] it is known, that the largest displacements appears on the chisel edge.

A linear elastic material model for the drill is assumed in the presented model. From this assumption it follows that after the deformation the chisel edge will still have a straight line form. By neglecting deformation of the chisel edge length, it can be considered as a rigid body, in the frame of the accepted material model. Like any rigid body, the chisel edge has six degrees of freedom. Practically, the chisel edge represents a segment, fixed by the two end points, one of them is situated close to the axis of the drill and the second one is situated on the periphery. The practice shows that the first point does not have an appreciable displacement, because of the symmetry of the loads relatively to the drill axis. Therefore, it is enough to describe the position of the chisel edge only by three coordinates of the second point. It is widely used to denote chisel edge position after the deformation by radial, angular and axial deflections [4,5]. As far as the stresses and strains are concerned, they have usually local character at the loaded chisel edge.

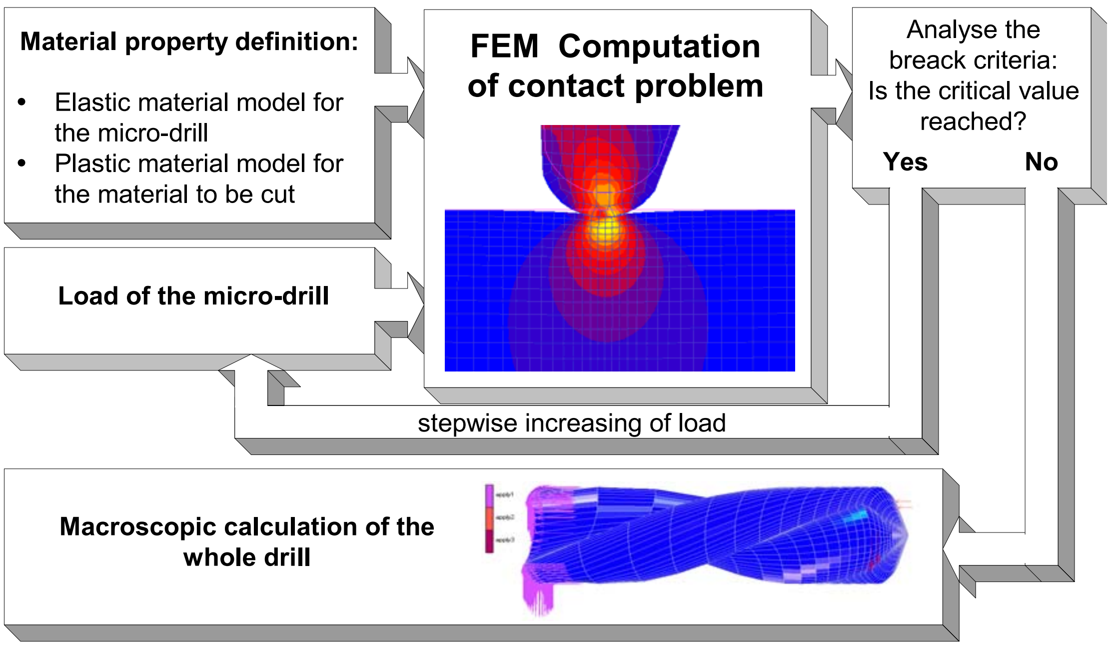

Fig. 1: Computation algorithm

The schematic structure of the developed mathematical model for twisting calculation is shown in **Fig. 1.** The calculation process is divided into two parts: the first one, so-called local problem, considers the processes taking place at the chisel edge, and is needed to define boundary conditions. The second one, called global or macro problem, calculates directly required twisting parameters like radial, angular and axial reflections by applying finite elements method (FEM).

The first model represents FEM formulation of a contact problem of two bodies, where the first of them, the wedge-shaped body (upper body in the **Fig. 1**), represents a cross-section of the chisel edge and the second one is a billet to be drilled (lower body in the **Fig. 1**). The wedge is loaded and acts on the billet. The load is increasing stepwise until the break criteria is reached. This is a kind of computation with a closed-loop. After satisfying the break criteria, the critical loads will be fixed and used in the solving of the macro problem.

The model of the macro problem is a FEM formulation of the whole drill. The boundary conditions are represented by a rigid fixation of the drill shaft and the loads, following from the solution of the local problem.

2.2 Local model

As it is already notified above, the local problem represents the acting of the chisel edge on the billet to be drilled. The solution of the problem allows obtaining the required critical loads for cutting the billet material. The coating plays the most important role in the model, because it modifies geometry of the chisel edge, makes it more blunt. It conditions greater critical loads to reach a break criterion in the billet. The geometry of the chisel edge cross-section and its attack angle also influence the critical loads.

The contact model is developed with following admissions:

- The model is admitted to be static;

- The friction of the chips as well as the friction in the contact are not taken into account. There is no possibility to take the friction into account in the frame of a static model because the friction itself depends on velocity;

- Drill heating and temperature changes of the mechanical properties of the drill material as well as the material to be cut are not taken into account. The drill heating itself is determined to a great extent by fracture processes taking place due to drilling. After some transition processes, the heating can be considered as stationary. By knowing the required boundary conditions, the heating can be solved in the frame of the static model;

- The contact problem is shown in **Fig. 2** schematically. By neglecting the edge effects we can consider a 2-D mechanical contact problem. Such neglect is possible, because the sizes in the cross-section of the chisel edge are much less than the length of it in practice: stresses distributions are the same for each cross-section (see **Fig. 2. a**.). The FEM model for the contact problem is developed for the MARC-MSC solver that supports contact treatment. As boundary conditions the fixed displacements on the bottom side of the billet and stepwise displacements on the upper side of the wedge are applied like it is shown in **Fig. 2. b**.

A non-linear elastic-plastic billet material model with workhardening is used, because the stresses, taking place due to acting the wedge, exceed the yield stress. The billet material stress-strain curve, obtained by uniaxial test, is generalized to the 2-D case by applying the von Misses condition.

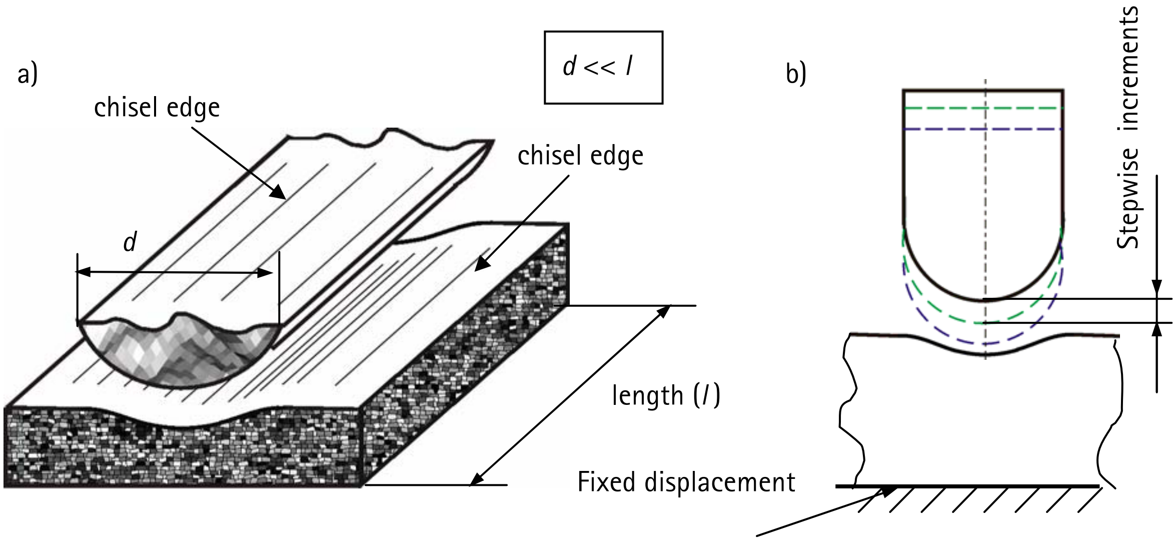

Fig. 2: Contact of the chisel edge and the billet: a) contact scheme; b) boundary conditions scheme at the contact problem formulation

The direct constraints are used to solve the contact problem in the frames of FEM technique. In this procedure, the motion of the bodies is traced, and when contact occurs, direct constrains are placed on the motion using boundary conditions – both kinematic constrains on transformed degrees of freedom and nodal forces.

A singularity problem can occur because only one contact point takes place at the touching moment. Therefore it is required to mesh the contact bodies finely at the touching area.

The choice of failure hypothesis depends on the billet material. There are criteria based on critical stresses, strains, energies and combined ones. It is also important how to compose failure hypothesis form stress and strain tensor components. For the brittle materials like glasses or stones, the shear components are decisive; for plastic ones like metals, the diagonal elements of the stress or strain tensors play a more important role [6]. Any failure hypothesis described above can be chosen in the frame of the developed model. The failure hypothesis will be computed for each node, the tree biggest ones will be found, averaged, and compared with the critical value. If the critical value is not reached, the loads will be increased and the whole process will be repeated until satisfying the break criteria. A special pre-processor for MSC-MARC solver was developed to carry out the calculation process automatically.

2.3 Macro model

The macro model deals with FEM simulation of the whole micro-drills and includes several parts: drill geometry generation, material model definition and boundary condition setting. As it is already notified above, the main aim of the presented model is to predict the radial, angular and axial deflexions of the chisel edge.

The geometry of the drill is quietly complicated and can differ by different producers. Some generalized geometrical characteristics of the drill is enumerated below:

Drill Diameter is the diameter over the margins of the drill measured at the point;

Margin is the cylindrical portion of the land which is not cut away to provide clearance;

Helix Angle is the angle of the leading edge of the land with the axis of the drill. The helix angle is identical with the rake angle of the cutting edges at the periphery of the drill;

Point Angle is the angle included between the cutting lips projected upon a plane parallel to the drill axis and parallel to the two cutting lips;

Land Width is the distance between the leading edge and the heel of the land measured at a right angle to the leading edge at the point end of a drill;

Chisel Edge Angle is the angle included between the chisel edge and the cutting lip, as viewed from the end of the drill.

The micro-drill coating can modify geometrical characteristics, and for small drills. This modification should be taken into account. Non-uniform distribution of the coating represents some difficulties by building a geometrical model of the coating (see **Fig. 3**). In **Fig. 3** the cross-section of a coated micro-drill is represented under three different enlargement degrees. It is possible to recognize that the coating thickness is larger on the external surfaces and smaller on the internal ones. Such coating distribution inequality is related to coating deposition technology.

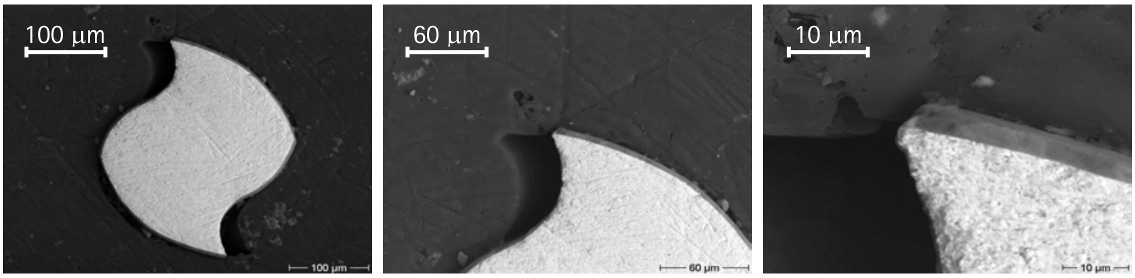

Fig. 3: Coated drill cross-sections: three enlargement degrees

As boundary condition the fixation of the drill shank and loads of chisel edges calculated by model described above are applied. The linear elastic material model for the drill material as well as for the coating is used. A special preprocessor was developed to generate FEM drill geometry and apply boundary conditions and material properties automatically.

3 Results and discussion

A contact problem with a steel billet and a TiN chisel edge is described below. The chisel edge is pressed in the billet stepwise with an increment of 0.006 μm. TiN has five-time higher Young's module as steel that allows considering the chisel edge as a rigid body.

Special attention is paid to study the influence of the chisel edge curvature radius. The investigation is carried out for four curvature radii (r_e) of 1μm, 2μm, 3μm and 4μm, which correspond to radiuses in reality.

In the **Fig. 4. a** the maximal von Missis equivalent stress, arisen in the billet body, is shown as a function of chisel displacement (chisel displacement is indicated in increments). As usual, the maximal stresses appear at the place of the contact. Of course, the stress increases with increasing the edge displacement increments. Acting the chisel edges with smaller curvature radius causes stress increasing because of less contact area. The deviations in the graphics, especially at the small displacements, are conditioned by singularity. The run of the curve has a linear part at its beginning with saturation part for the large displacements that corresponds to stress-strain dependence of the billet material and means linear strains increasing with the edge displacements in the contact area.

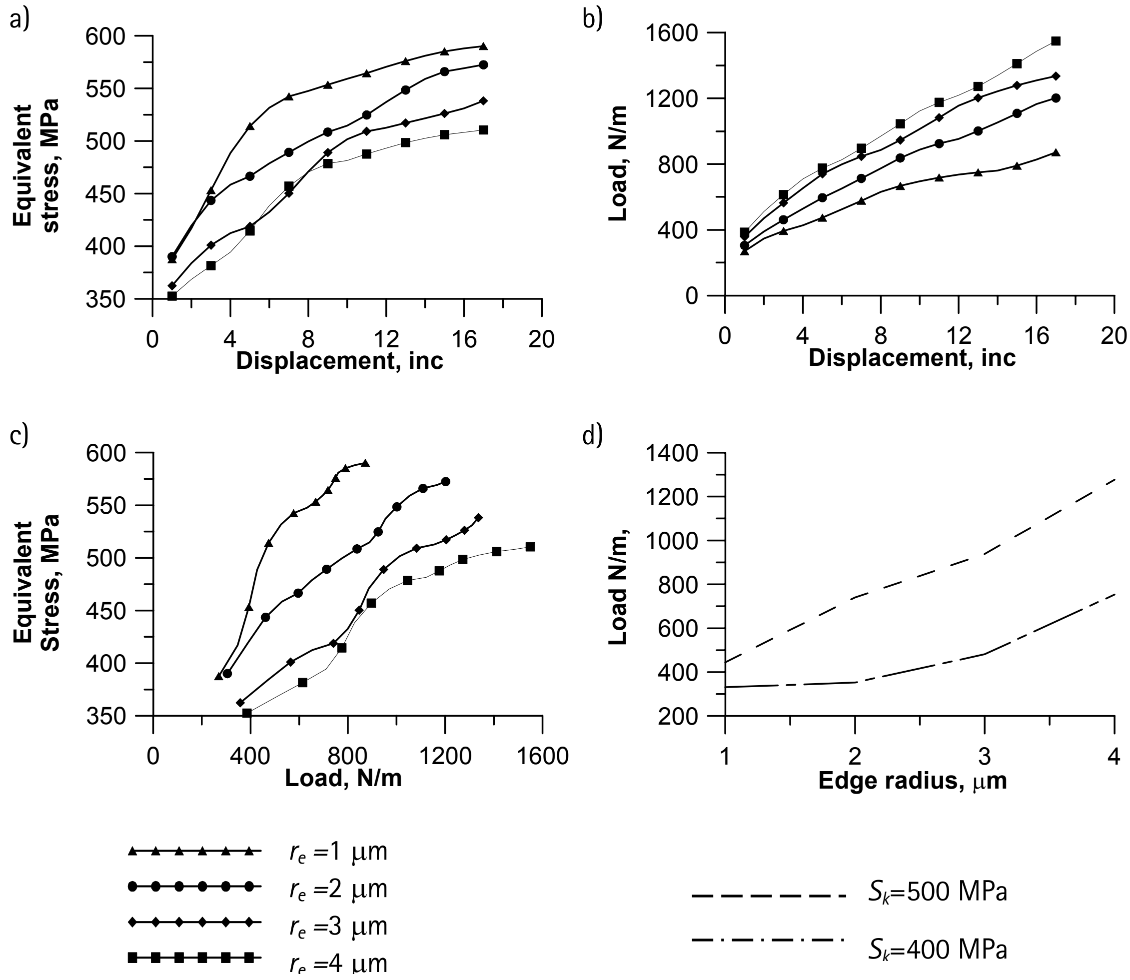

Fig.4: Local problem study: a) stress-strain dependence; b) load – strain dependence; c) stress-load dependence; d) critical stress – chisel edge radius dependence.

The required force on the upper chisel edge side to make a displacement possible is indicated on **Fig. 4. b**. Less force is required for edges with smaller curvature radius to do some displacement.

The maximal von Missis stresses in the billet as a function of loads is shown in **Fig. 4. c**. It is needed to spend less afford to reach some stress level in the billet. Evidently the cutting process is better to carry out having a sharp tool. The stepwise deviation on the graph can be explained by discrete nature of FEM models: the contact area is increasing with pressing-in displacement steps but we can bring in the contact whole element, only. Therefore the spasmodically increasing of the contact area at the introducing a new element into contact causes deceleration of the stress increasing.

Fig. 4. d represents the required force dependences to reach some stress level on the edge curvature radius. The dependences are calculated for von Missis equivalent critical stresses S_k of 500 MPa and 400 MPa dashed and dash-and-dot lines respectively. The dependence calculated for 500 MPa is linear. Such behaviour can be explained by the fact, that the contact surface grows linearly with growing of chisel edge radius. The dependence calculated for the critical stress 400 MPa differs from linear behavior in the domain of little radiuses. This effect can be related to the scaling of the process. Let us consider contact of two chisels edges, a small and a big one, see **Fig. 5.** The characteristic contact area can be imaginary divided into two parts: confident contact (shown as a black line) and pseudo contact (shown as a grey line). The pseudo contact area takes place because of elasticity and can play a noticeable role only if its size is comparable with the chisel edge radius. The pseudo contact area increases the whole contact area. This determines a greater force to reach a required stress level as predicted by linear dependence.

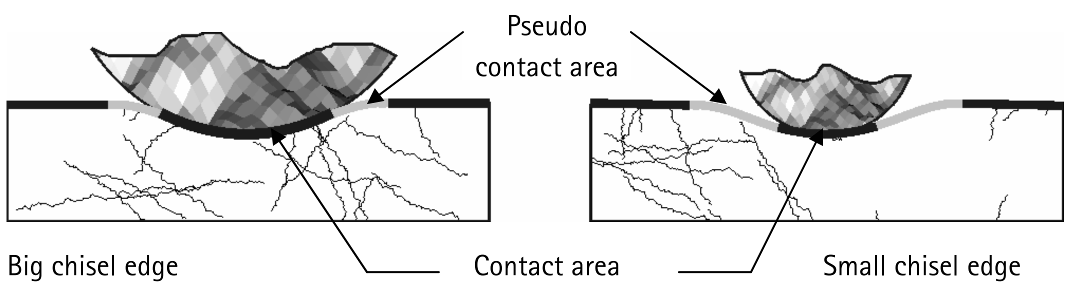

Fig. 5: Chisel edge contact scheme: sizes influence.

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