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The correct way of splitting tools – Optimization of instrument design for measuring contact stress distribution

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Abstract

Contact stress on the tool has been measured with a split-tool apparatus that has a poor resolution of the stress distribution, and with photoelastic tools that cannot be used with real cutting parameters since the materials are too weak. This paper presents an improved split-tool design allowing continuous stress distribution dataset instead of discreet steps by using a tilted separation plane between the tool tip and the tool body. This paper optimizes the separation plane angle with 3D-FEM to minimize deflection.

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1. Introduction

Contact stresses have a strong influence on tool wear and tool deformation in metal cutting. Additionally, the stresses affect friction on the tool-chip interface and the heat flux from the chip to the tool. Regardless of the importance of the contact stresses, there is no good, established method to measure the stresses. The methods used in the literature are photoelastic tools and split tool apparatuses.

Usui and Takeyama (1960) were among the first researchers to apply photoelastic materials to cutting tools [1]. Photoelastic tool forms isochromatic patterns visible under polarized light. The patterns on the tool follow the principle shear stresses. The drawback of this method is that photoelastic materials do not have the strength to withstand cutting
conditions on productive cutting parameters.[2] Bagchi and Wright (1987) show that sapphire can be used as a photoelastic tool with relatively high cutting parameters while machining carbon steel AISI 12L14 ($\sigma_y = 490$ MPa)[3].

The split tool apparatus is a two-part tool, where the rake face is divided with a separation plane. By controlling the thickness of the lower part, the forces acting on it change corresponding to the stress distribution. The original design of the split tool had uniform geometry through the thickness of the tool and the thickness of the lower part was modified by using multiple tools or grinding single tool thinner after every measurement. A similar design has been used for example in Kato et al. (1972), Barrow et al. (1982), Lee et al. (1995).[4–6] The original split tool is often credited to Zorev (1963), but the referred paper does not mention split tools [7]. The earliest reference available for reading in this topic that was found by the author is by Gordon (1967) [8]. Gordon has been credited also in Zorev (1966) to use split tool in paper written in Russian by Klushin and Gordon in 1952 [9]. The split tool concept is presented in Fig. 1. More advanced design of the split tool is presented by Childs et al. (1989) where the separation plane is tilted so that looking from the rake face, the separation plane forms a wedge shape on the tool, as illustrated in Fig. 2 [10].

The design developed in this paper (Fig. 3) is somewhat a combination of the latter two, where the wedge shape from design 2 is tilted to a smaller angle, but the tool is still clearly split in the orthogonal direction. The benefit of this design compared to the design 2, is that the transition from loading the different tool halves is smoother and thus the required uncut chip thickness is smaller. The benefit compared to design one is that the loading transition between the tool halves is continuous instead of piecewise, and the zero loading can be reached. The difficulty with this design is the tool half nearer to the cutting edge that is left relatively thin by necessity. In order to address this issue, this paper optimizes the wedge angle $\Delta \beta$ to minimize the deflection of the tool halves. The optimization is done by running 3D-FEM simulations of the designs with different edge geometries. The optimization criterion is “resultant” deflection, i.e. a square root of summed 2nd-powers of the maximum deflection on each tool half. Additionally, 0.03 mm was set as a failing criterion for combined maximum deflection for both tool halves, that was chosen based on the gap between the tool halves that is 0.03 mm. In layman’s terms, the tool halves are not allowed to touch.

![Fig. 1 Split Tool concept with contact lengths notated](image1)

![Fig. 2 Advanced split-tool design](image2)
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Fig. 1 Split Tool concept with contact lengths notated Fig. 2 Advanced split-tool design

Fig. 3 New split-tool design

2. Simulation setup

The simulations were done with a Scientific Forming Technologies Corporation Deform implicit Lagrangian FEM solver. The optimization was done by simulating the tool with 7 different wedge angles ($\Delta\beta$ in Fig. 3) in 4 degree intervals from $11^\circ$ to $35^\circ$. The maximum tool deflections were measured from the cross section at the transition point where the lower tool contact length approaches zero. The work material is AISI 316L and the tool material is WC-10%-Co.

The workpiece was meshed with 99523 tetrahedral elements. The tool was divided in to 4 parts to make individual meshes for tool tips that are in contact with the workpiece and tool bodies that do not require as high simulation precision. The division is presented in Fig. 4. The upper tool tip was meshed with 47589 elements, the upper tool body with 38555, the lower tip with 86976 and the lower body with 36323 elements.

The workpiece was modeled as plastic using the default model from Deform material library for AISI 3016L. The work material response was not considered critical since the optimization criterion is not sensitive regarding the material, only the absolute value of the deflection would change. The boundary conditions were restricted movement to all directions to the bottom surfaces of the tools, and restricted movement on x-z-plane for the outer surface of the workpiece whilst the y-direction was set for cutting speed. Coulomb friction was set to 0.5 between all surfaces. The tool was modeled as elastic using material properties presented in Laakso et al. (2017) [11].

The cutting parameters were $v_C = 140$ m/min, $a_p = 0.2$ mm and sideways feed $v_f = 240$ m/min. Simulation runs 4000 steps with a time increment of $10^{-6}$ seconds. Total simulation time varied from 33 hours to 78 hours. The high sideways feed was selected in order to simulate short cutting length. The sideways feed was tested also with a 0 m/min value and cutting forces were not affected significantly by the high feed value in comparison.
3. Results

The simulation results show continuous relation between the tool deflection and wedge angle. With an increasing wedge angle, the lower tool deflection decreases exponentially and the lower tool deflection increases slowly and almost linearly. Fig. 5 presents the optimization criteria and the chip formation during the simulation. Fig. 6 shows the effective stress distribution on the tool edges, with maximum value at 5290 MPa. This value is alarming considering the tool materials yield stress that is 4700 MPa. Fortunately, the high value of stress is numerical error caused by infinitely sharp tool edge and the more trustworthy value is the average stress, which is around 3000 MPa at the tool edge.

Including the cutting edge roundness in the simulation would have increased the simulation time exponentially since the required element size would have been extremely small. The displacement distribution is shown in Fig. 7, where it can be seen that the deflection of the tool is strongly localized around the contact point between the chip and the tool. The optimization results are shown in Fig. 8, where the deflection is plotted against the wedge angle. The optimal point can be seen around 31°.

![Fig. 5 Simulated chip formation and optimization criteria](image)

\[ D_{tot} = \sqrt{d_{up}^2 + d_{low}^2} \]
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4. Discussion and conclusion

Optimized tool geometry with 31° wedge angle should withstand cutting experiments with materials that have flow stress equal to AISI 316L. The maximum deflection of the tool was found to be 0.0165 mm that is well below the allowable limit of 0.03 mm. Future work should be done with a full elastic-plastic material model of the WC-10%-Co for the tool, to investigate possible plastic deformation and creep during the experiments. In addition, a longer simulation should be done to investigate the effect of the cutting temperature on tool deflection. The design can be moved to prototyping- and testing phase after more detailed simulations.

References