Optimisation of Cutting Tools using CA-Technologies

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Abstract. *Machining of metals using the **M**inimum **Q**uantity **L**ubrication (MQL), airflow with mixed oil droplets, is gaining more and more importance. MQL machining is environmentally friendly and enhances cost efficient production. Besides the adapted machine tool, the generation of the lubricant, and the chip evacuation, the suitable tool design is of significant importance. Basis for the development of high performance drilling tools is the use of CA-Technologies with the generation of a CAD model, FEA of static property and dynamic behaviour and **C**omputational **F**luid **D**ynamics (CFD) of flow calculation. Laboratory tests with real-time thermal imaging, high-speed imaging, recording of cutting force and evaluation of the produced work piece (geometry, surface and chip formation) serve as a check for the capability in practice and the comparison of simulation and experiment.*

Keywords: *High-Performance-Cutting, Optimisation, Minimal-Quantity-Lubrication, CA-Technologies*

1 INTRODUCTION

Reliability of the production process is pre-condition for the acceptance of a new technique. The simple substitution of the conventional lubrication (often some 1,000 l/h) by MQL (some ml/h) doesn't lead to success. High performance tools are required in order to achieve the highest productivity demands. This requires tool designing under maximum utilization of all three available resources like cutting material, macro and micro geometry of the tools and coatings.
CA-technologies allow the development of **H**igh **P**erformance **C**utting (HPC) tools with higher accuracy, in shorter time and with less (expensive) tests. The simulation of several possible solutions in consideration of worst-case conditions allows the selection of the best design and optimising it in further steps.

Coming from a well-tried tool, a CAD-Model of a modified twist drill is generated and transferred to a FE-Model. By using mesh-models the stress, strain and deformation characteristics can be calculated. The path of the lubricant is calculated by CFD: Starting from the entry into the shank of the tool, through the internal coolant ducts, to the exit at the tool flank (= entry in the flute), through the flute and to the exit of the work piece.

2 OPTIMIZATION OF CUTTING TOOLS

2.1 Entry of lubricant into the shank

Requirements were: Avoidance of idle volume, tightness between the feeding screw and the tool shank, simple handling and economical production. Different shank end geometries were investigated (Figure 1).

(a) (b) (c) (d)

Figure 1: Investigated shank types.

a) Planar end without slot and planar screw.
b) Planar end with sickle shaped slot to connect the both coolant ducts.
c) Conical end with round slot and conical screw.
d) Stepped end (labyrinth seal) without connecting slot and with corresponding screw with index pins for the orientation of the coolant ducts.

In a first test the leak tightness of the different shank end geometries was compared. During a time of one hour and at a spindle speed of 10,000 rpm the MQL was switched on in intervals: for 5 seconds on and for 2 seconds off. The designs a) and b) caused oil contaminations in the clamping area. The conical end and labyrinth seal yield the best leak tightness.

In a second test the continuity of the amount of spray and the reaction time of the different shank end geometries was compared. For testing these properties special designed equipment was used. It allowed recording of the oil mist continuity and the reaction time in a running spindle. To accumulate nearly the whole oil mist quantity of the radial jet, the tool extends into an axial slotted tube. The inside of this tube was lined with blotting paper to collect the MQL jet (Figure 2). During the ZY-traverse path of the machine tool, the MQL supply was activated and deactivated.

After the spray test, the rolled up plane blotting paper showed spray images, dependent on the shank end geometry (Figure 3).The evaluation of the spray image under consideration of the signal of the positioning control of the tool machine allowed to determine the reaction time of the total system and showed the continuity of the MQL jet. The conical end yields the best results. Therefore for further investigations and optimisations only this design was considered. At the conical end four different slot shapes were considered: a) round and narrow, b) round and wide c) trapezoid and d) convex (Figure 4).

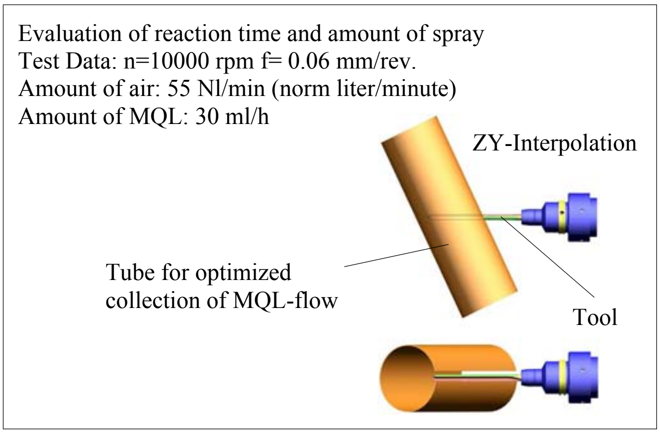


Figure 2: Equipment for MQL spray tests.

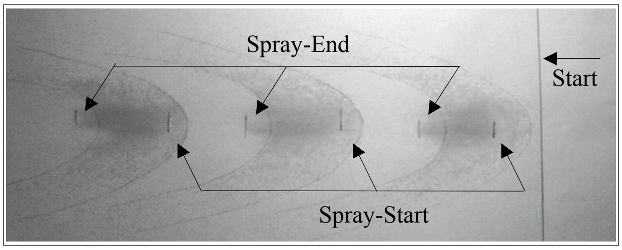


Figure 3: MQL spray Image.

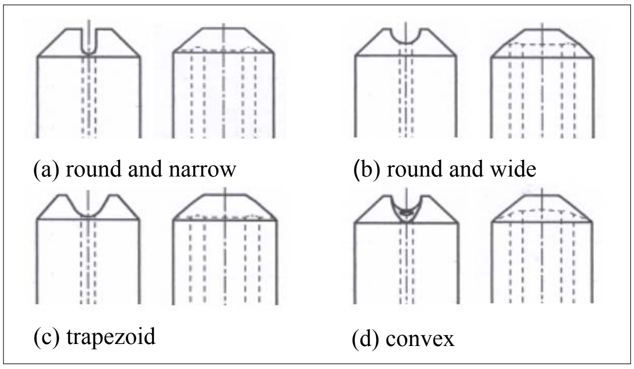


Figure 4: Slot shapes.

CFD analysis in the connection area of the shank end and the adjusting screw (Figure 5) could give the needed information for the final decision.

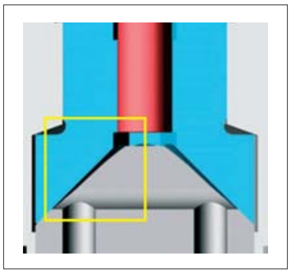


Figure 5: Connection area.

Figure 6: Round, wide slot.

The flow profile of MQL for the conical shank end with the round wide slot (Figure 6) in the connection area of the shank end and the adjusting screw is shown in Figure 7. The turbulences were clearly less than those of the other designs.

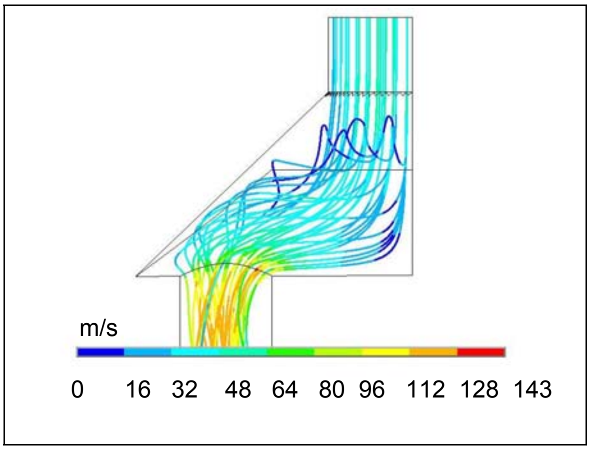


Figure 7: Flow profile at shank end.

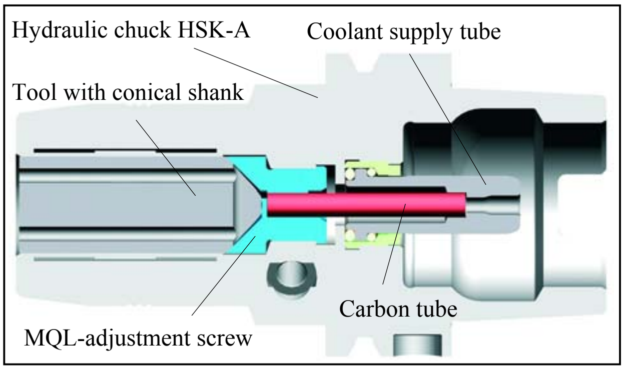


Figure 8: Assembly of the MQL discharge.

Additionally, this solution allows the simplest handling and causes the lowest production costs. Figure 8 shows the assembly of the best suitable design. This solution was proposed to the German Institute for Standardization (DIN).

2.2 Flow of lubricant into the flute of the tool

The results of Fluid Dynamic Calculations clarified the differences of the flow conditions of emulsion and MQL. For the calculation the diameter of the duct was set to 2.4 mm and the length to 113 mm. The mean value of the flow velocity in the flute of the tool using MQL amounts to 30.4 m/s, using emulsion 3.5 m/s. For the calculation of the flow velocity the single rates were integrated over the flute area. The volume flow using MQL amounts to 6,960 Nl/h (norm litre of air per hour), using emulsion 600 l/h (Figures 9 and 10).

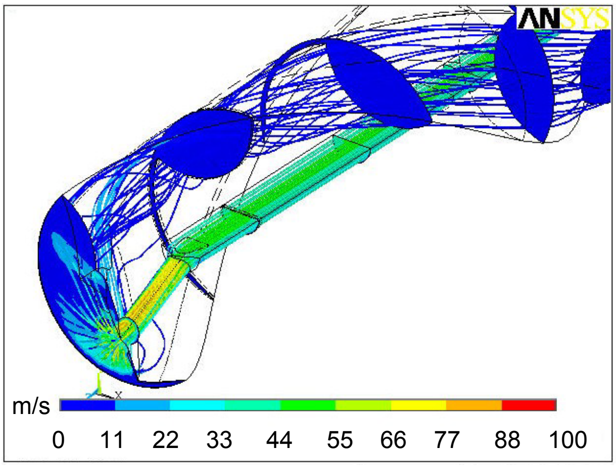


Figure 9: Flow velocity – emulsion.

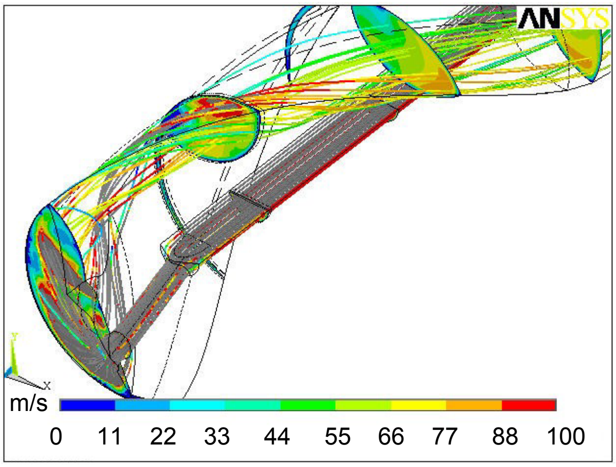


Figure 10: Flow velocity – MQL.

Step drills and reamers have ducts with additional outlets on the cutting area of the steps and also at the lands to reduce their friction at the wall of the hole. To have a basis for such tool design and to ensure that the lubricant reaches the relevant acting areas, the flow velocity was calculated depending on the diameter and length of the duct. Basis of the calculation was adiabatic pipe flow under consideration of resistance in pipes. The comparison of the CFD calculated values with the measured values of a practical test shows a close correlation (Figure 11).

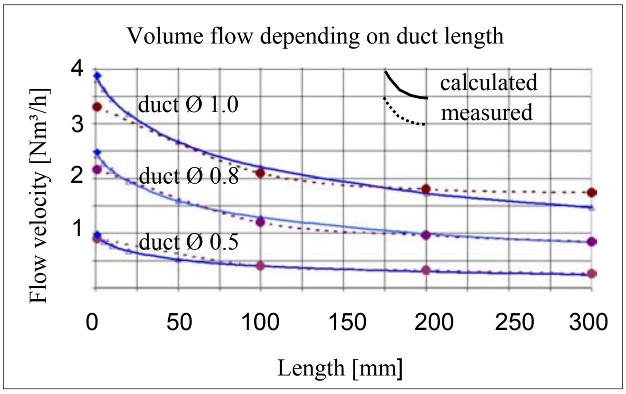


Figure 11: Volume flow comparison.

2.3 Entry of lubricant into the flute of tool

Why are the flow velocities and the volume flows so much higher using MQL?

Water is nearly incompressible i.e. the density is nearly unchanged by pressure. On the path from A to B the emulsion undergoes a drop of pressure, because it flows into the flute. Due to the nearly consistent density, the drop of pressure causes no expansion of volume. Therefore the flow from A to B has a consistent flow velocity.

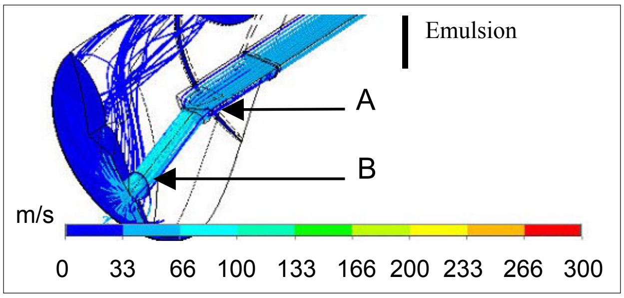


Figure 12: Flow velocity into flute – Emulsion.

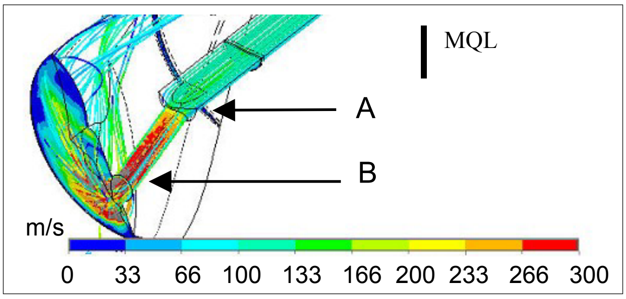


Figure 13: Flow velocity into Flute – MQL.

Air is compressible. On the path from A to B the MQL flow undergoes a drop of pressure as well; however the air expands and enlarges its volume. Consequently the flow velocity increases considerably. (See gradient of flow velocity in Figure 13.)

2.4 Exit of lubricant from the work piece

A major property of the function of drills is the ability to transport the chips through the chip flute out of the hole. Mainly holes with a large ratio length / diameter are a special challenge. Besides the geometry and the cutting data, chip evacuation strongly depends on the amount of volume flow. A practical test with a spiral-fluted drill could clarify the chip motion.

The analysis of an image sequence, recorded by a high-speed camera, enabled to calculate the speed of the chips while leaving the work piece.

Test conditions: Solid carbide drill with spiral flutes.

Drill diameter:	6.0 mm	Pitch:	30° (44 mm)
Drilling depth:	15×D	Material:	AlSi9Cu3
Feed:	0.12 mm/rev	Spindle speed:	6,475 rpm
Lubrication:	MQL		

Calculated from the machining data (spindle speed, pitch and diameter) the transportation speed is 4.76 m/s, caused by the helical pitch of the drill. The speed of the chips, calculated on the information of the high-speed image sequence is 7.06 m/s (Figure 14).

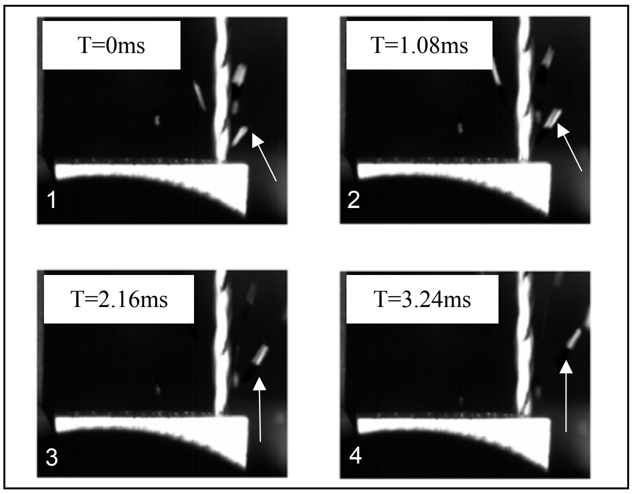


Figure 14: High – speed images of chip flow.

The maximal speed, the chips can reach is either the transportation speed caused by the helical pitch of the drill or the speed of the lubrication medium. The higher flow velocities and volume flows of MQL shows the advantages over emulsion.

MQL comprises mainly air (some cubic metres of air and some millilitres of oil per hour). Therefore MQL requires small chips. This can be influenced by the geometry of the cutting lips, the rake angle of the drill and the cutting data.

2.5 Enlarged flutes

Particularly when drilling deep holes, the chips need enough space in the flute of the tool on the path from the cutting area (in the depth of the hole) to the exit of the work piece. This also applies when using HPC with a high rate of metal removing. A solution to expand the space available for the chips is enlarging the flute from the tip to the shank (Figure 15).

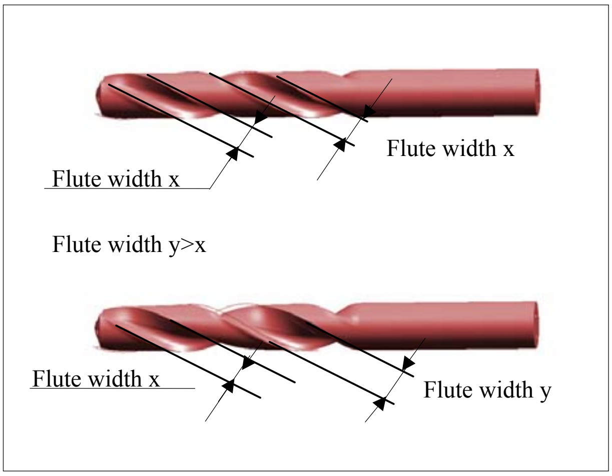


Figure 15: The flute profile.

Figure 16 (a).

Figure 16 (b).

The enlarged flute cross-section facilitates the chip evacuation considerably. However this flute design excludes carbide rods with two twisted coolant ducts. A central duct with Y-shaped exits in the flank (Figure 16a) allows more freedom in designing the profile of the drill than two spiral ducts (Figure 16b).

Enlarging the flute cross-section causes necessarily a reduction of the bending strength of the tool (Figure 17). Therefore the exploitation of the full capability of these high performance tools requires stable machining conditions.

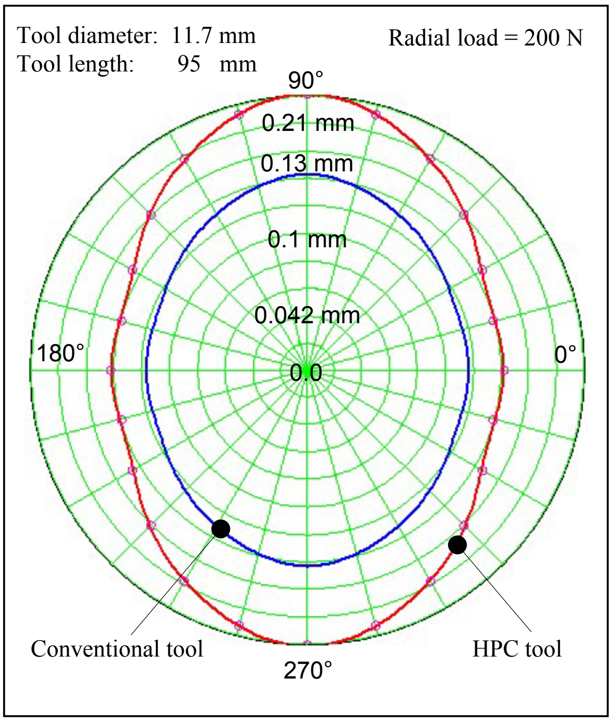
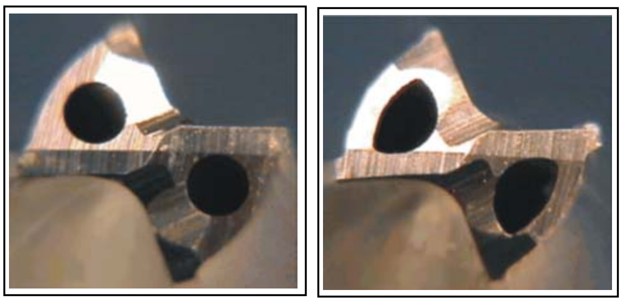


Figure 17: Calculated displacement as a function of rotation angle.

2.6 Optimisation of the coolant ducts

A major influence on the lifetime of the tool is the heat, caused by the cutting process. Higher temperatures accelerate diffusion and adhesion whereby the lifetime drops. Besides the cutting parameter, the temperature depends strongly on the amount of coolant flow. Especially for small diameters the volume flow is limited by the available space for the coolant ducts. Circular ducts cannot be expanded adequately because the wall to the flute and to the outer diameter would become too thin for the mechanical load caused by the cutting process. At straight fluted drills an alternative is to replace the conventional ducts with Trigon ducts, having almost a triangular or elliptical shape (Figure 18).



(a) Conventional. (b) Triangular.

Figure 18: Cross sections of coolant ducts in straight fluted drills.

The aim was to maximize the cross section of the ducts and to retain the mechanical stability of the tool. The optimal dimensioning of these Trigon ducts is a result of the Finite Element Method: stress in the cross section (Figure 19) and torsion 4×D behind the cutting tip (Figure 20).

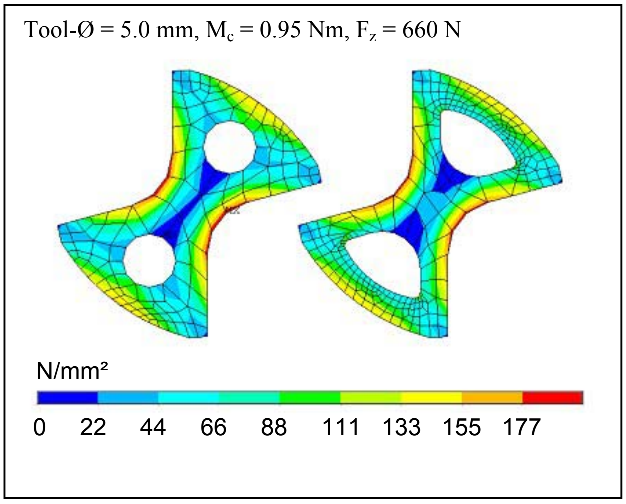


Figure 19: Stress in cross section.

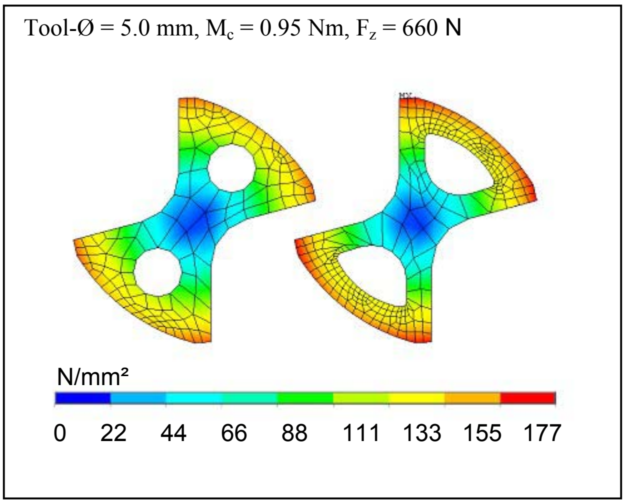


Figure 20: Torsion 4xD behind the cutting tip.

The tool properties retain almost the same stiffness and resistance against bending where as the size of the coolant duct cross-section increases by over 50 %. (Figure 21). The higher volume flow is able to distinctly dissipate more heat created by the machining process. Moreover there is a better lubricant supply to the cutting area and therefore an increased lifetime of the tool.

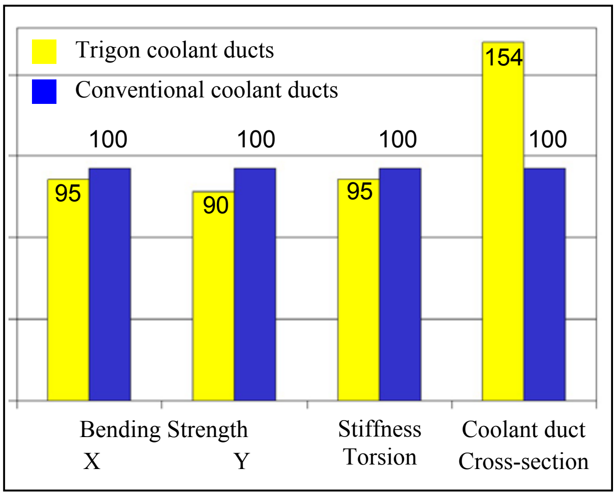


Figure 21: Tool properties in %.

Summary

The combination of lubricant flow simulation, FEA of mechanical properties and practical machining test leads to the design of optimised tools which meet the high requirements of progressive machining technologies.

CA Technologies can help to reduce developing time and costs. They also contribute to gain deeper and verified knowledge about the processes.

3 REFERENCES

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