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Additive manufacturing of an internally cooled tool holder for turning

Eckart Uhlmann[1,2], Julian Polte[1,2], Janek Fasselt[1], Christian Schmiedel[1], Benjamin Hein[1], Nicola Welteke[1]

[1]*Fraunhofer Institute for Production Systems and Design Technology IPK, Germany*
[2]*Institute for Machine Tools and Factory Management IWF, Technische Universität Berlin, Germany*

janek.fasselt@ipk.fraunhofer.de

Abstract

Additive manufacturing enables fundamentally new design concepts for complex thermal management systems. This paper describes the development of an additively manufactured internally cooled tool holder for turning. A novel approach for internal cooling was applied based on Triply Periodic Minimal Surfaces (TPMS) structures and the expansion of liquid carbon dioxide (CO_2). The heat transfer properties of the TPMS structures were assessed prior to production by simulation. The tool holder was then additively manufactured from 1.4404 (316L) stainless steel using laser powder bed fusion (PBF-LB/M). Experimental tests on the tool holder showed a temperature drop of $\Delta\vartheta_S$ = 115 °C at the cutting edge compared to an uncooled version. Initial use in turning tests proved the functionality of the overall system.

1. Introduction

In response to escalating environmental concerns, the industrial sector is being forced to reduce its environmental impact. Cooling lubricants, essential to machining processes, are a significant contributor to environmental pollution. However, CO_2, traditionally considered a greenhouse gas, has emerged as a dual-use substance when captured in industrial processes, offering both environmental friendliness and climate neutrality. The following paper presents the development of an additively manufactured tool holder with integrated internal cooling based on CO_2 for turning.

In metal cutting processes almost all energy is being converted into heat [1]. In order to effectively cool the shear zone, new concepts for internally cooled tools must be developed. Targeted cooling at the cutting zone can enable higher cutting speeds v_c and thus shorten process times t_P or enable the machining of difficult-to-cut materials such as hard metals. FRANCA ET AL. developed a tool holder with an internal channel, demonstrating a reduction of cutting temperatures ϑ_c up to 21.52 % at the shear zone compared to dry machining, with the tool holder proving particularly efficient at higher cutting speeds v_c [2]. MINTON ET AL. investigated the formation of hot spots during dry and near-dry turning of grade 2 titanium using conventional cemented carbide inserts. The successful diffusion of heat and inhibition of wear in titanium machining through an internally cooled tool with a diamond-coated insert, providing longer tool life and high surface finish without external coolant was demonstrated [3]. GHANI ET AL. developed three additively manufactured tool holders with internal channels for the cooling fluid by powder melting and sintering methods. They found that powder melting provides higher precision and exhibits better surface roughness inside the internal channels than sintering methods [4]. In this paper, a tool holder with an internal evaporation chamber with integrated TPMS-structures for the expansion of liquid CO_2 is developed and additively manufactured by PBF-LB/M.

2. Development of tool holder

At the beginning of this work, the tool holder with the expansion chamber for the CO_2 with integrated TPMS lattice structures was modelled. Simulations were then carried out to validate the design. For the experiments, the tool holder was manufactured using PBF-LB/M and applied in temperature tests with a heating cartridge as well as turning tests.

2.1. Design of tool holder

In order to increase the heat exchange surface on the inside, surface-based lattice structures have been used. Compared to strut-based lattice structures, surface-based lattice structures have a wide range of advantages in the specific application of heat transfer with simultaneous high requirements for strength and rigidity of the overall system. The TPMS surface structures used consist of infinite, non-intersecting periodic surfaces in three main directions. Due to their many undercuts and highly integrated architectures, these structures can only be produced using additive manufacturing. Compared to strut-based lattice structures, the absence of nodes results in higher mechanical resistance to material fatigue. Stress peaks due to the periodic nature of the surfaces are avoided. They also allow a significant increase in surface area A_s compared to other lattice structures, while providing favourable internal fluid-mechanical behaviour [5]. However, the modelling and adjustment of porosity Φ, wall thickness t and cell size a cannot be modelled in conventional CAD programs. RHINOCEROS, from ROBERT MCNEEL & ASSOCIATES, Seattle, USA, was used with the GRASSHOPPER plug-in. Formula (1) was used to develop gyroid TPMS lattice structures.

$$\cos x \sin y + \cos y \sin z + \sin x \cos z \qquad (1)$$

Cooling of the shear zone is enabled through the expansion of liquid CO_2 inside the tool holder on the basis of the Joule-Thomson effect. The overall system therefore requires an inlet and outlet for the CO_2, as well as an expansion chamber with heat exchanger structures. The model is shown in Figure 1. Inside the expansion chamber, heat is exchanged with the CO_2

by forced convection. The process heat generated by friction, when the cutting edge engages with the workpiece, is transferred to the expansion chamber by conduction. In addition to indirect cooling, direct cooling can be achieved by screwing in a nozzle directed at the shear zone.

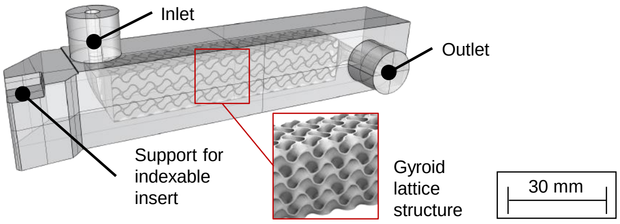

Figure 1. Tool holder with internal gyroid lattice structures

2.2. Simulation of tool holder

Various simulations of cooling scenarios were then carried out using the CAD model in Discovery from ANSYS INC., Canonsburg, USA. First, the simulation was considered using purely passive cooling. For this purpose, in the area of the cutting edge, a heating power of $P_H = 50$ W was applied. This corresponds to the values determined in previous heating power P_H determined in previous tests using thermocouples in the cutting edge of the tool by the penetration into the aluminium workpiece. An ambient temperature of $\vartheta_U = 22$ °C was also applied. It was found that the tool holder with the gyroid lattice structure shown in Figure 2 has a lower temperature at the cutting edge of the tool by $\Delta\vartheta_S = 184$ °C compared to a cavity.

Workpiece material:		1.4404 (316L)
Ambient temperature:	ϑ_U	22 °C
Heating power:	P_H	50 W
Tool holder dimensions:	l x w x h	125 mm x 20 mm x 20 mm

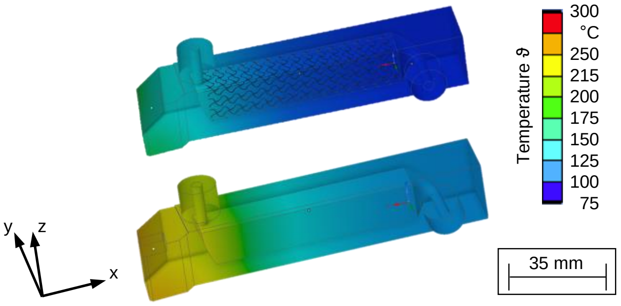

Figure 2. Simulation of passive cooling of the tool holder with gyroid lattice structure and without gyroid lattice structure

2.3. Experimental investigation

The preparation of the build job for the additive manufacturing of the tool holder was prepared in the QUANTAM software from RENISHAW PLC, Wotton-under-Edge, UK. The model was aligned in the build space of the additive manufacturing system to avoid internal support structures. Following the preparation of the build job, the tool holder was additively manufactured from 1.4404 (316L) stainless steel on a RENAM 500Q from RENISHAW PLC. The additively manufactured tool holder was post-processed by separating it from the substrate plate using a band saw and removing the support structures. The side surfaces were blasted, the connections drilled out and an 1/8-inch thread was cut. The test setup for the heat tests essentially consisted of a CO_2 supply, an electronically controlled valve, a capillary and the tool holder with thermocouples. A heating cartridge with a heating power of $P_H = 40$ W was installed in the area for the indexable inserts on the tool holder, thus achieving temperatures ϑ comparable to those achieved in turning experiments done before. Figure 3 shows the temperature ϑ at four measuring points on the tool holder over time t. The measuring point at thermocouple 1 represents the shear zone on the indexable insert. During the cooling phase, the temperature at this point drops by $\Delta\vartheta_S = 115$ °C.

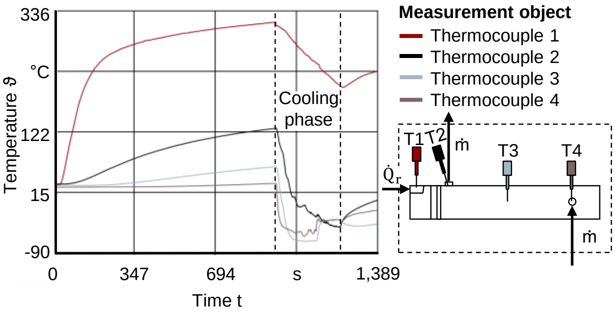

Figure 3. Temperature curves without and with active cooling

As shown in Figure 4, initial turning tests were carried out using the prototype tool holder. The shear zone was actively cooled via the rear connection with a nozzle.

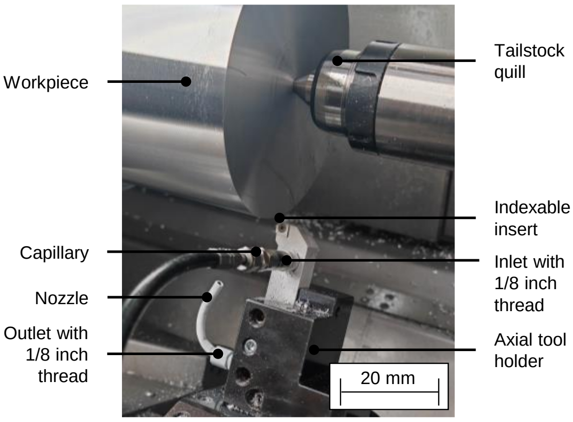

Figure 4. Cryogenically cooled tool holder in use

3. Conclusion

This paper shows the development of an additively manufactured internally cooled turning tool holder with TPMS structures for liquid CO_2 expansion. The use of surface-based lattice structures, specifically TPMS, offered advantages in heat transfer efficiency, strength, and rigidity. Simulations validated the design, and experimental tests demonstrated a substantial temperature reduction at the cutting edge. The successful implementation in turning tests confirmed the tool holder's functionality, highlighting its potential for improved machining processes through targeted cooling at the cutting zone.

Acknowledgements

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