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Enhancing cooling efficiency of WC-Co cemented carbides cutting tools with lattice structures fabricated by 3D printing

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Abstract

WC-Co cemented carbides, renowned for their exceptional hardness and durability, are widely utilized as tool materials, particularly in demanding applications such as cutting tools where high hardness and wear resistance are critical. However, this material displays relatively poor thermal characteristics, i.e. low thermal conductivity, often resulting in significant temperature increases near the cutting edges during machining, especially using aggressive cutting conditions. Additionally, this heat can cause thermal deformation, leading to reduced precision. To address this issue, this study explores methods to enhance the cooling efficiency of WC-Co cemented carbides tools without compromising their mechanical strength. The primary aim of this research is to improve the cooling efficiency of WC-Co cemented carbide tools. To this end, cutting tools with lattice structures were produced using WC-Co cemented carbides, employing a pellet-based 3D printing method. These lattice structures, designed to increase the exposed surface area of the tool, promote heat dissipation and, consequently, suppress temperature rise during hard machining. Several experiments were conducted to evaluate the performance of these samples. Observations of microstructures, along with measurements of hardness and density, revealed that tools manufactured by pellet-based 3D printing, while not fully matching those produced by conventional powder metallurgy, exhibited acceptable performance. Furthermore, cooling performance evaluation experiments validated the enhanced cooling performance of the lattice structures. Finally, actual cutting was performed to demonstrate that the fabricated tools are suitable for machining applications. This study confirmed that lattice structures created through 3D printing can enhance cooling efficiency while maintaining sufficient strength. These findings highlight the potential of 3D printing in creating advanced tool designs that effectively balance cooling efficiency and mechanical strength, paving the way for broader applications in high-precision machining.

Keywords: Cooling, Cutting, 3D printing, Tool

1. Introduction

High temperatures during the metal cutting process lead to tool wear, thermal erosion, dimensional inaccuracies, and increased surface roughness. Additionally, these temperatures contribute to the thermal deformation of the cutting tools, which is a major source of error [1]. WC-Co cemented carbides are widely used as materials for cutting tools due to their exceptional hardness and durability. However, this material has poor thermal properties like low thermal conductivity, often causing significant temperature increases at the cutting edges during machining, especially under aggressive conditions. Some research has been conducted to improve the cooling efficiency of cutting tools by innovating their structural design [2].

It has been demonstrated that lattice structures created through metal 3D printing increase surface area, thereby facilitating easier heat dissipation and exhibiting high cooling performance [3]. However, there are currently no examples of lattice structures being applied to cutting tools. The 3D printing of WC-Co cemented carbides using the SDS (shaping-debinding-sintering) process exhibits superior density and fracture toughness compared to other methods such as SLM (selective laser melting) [4]. Furthermore, WC-Co cemented carbides produced by pellet-based 3D printing, which is one of the SDS processes, can achieve nearly defect-free, fully dense structures by adjusting the manufacturing parameters, potentially matching those produced by traditional powder metallurgy [5]. However, there are currently no examples of leveraging the advantages of 3D printing to fabricate tools using WC-Co cemented carbides.

Building upon the findings revealed in these studies, this research focuses on fabricating cutting tools with lattice structures using pellet-based 3D printing of WC-Co cemented carbides. The primary aim is to improve the cooling efficiency of WC-Co cemented carbide tools. By leveraging the advantages of 3D printing to incorporate lattice structures into tool design, this study seeks to enhance cooling performance while maintaining the mechanical strength of the tools, thereby demonstrating their potential for advanced machining applications.

2. Method

In this section, the methods used for fabricating cutting tool inserts with lattice structures through pellet-based 3D printing are introduced, along with the experimental methods employed to evaluate their performance. The experiments conducted include measurements of hardness and density, cross-sectional observations, cooling performance evaluation, actual cutting, and observations of tool wear after cutting.

2.1. Tool fabrication

The fabricating process begins with the mixing of pellets used for 3D printing. The raw materials for the pellets and their weight percentage ratios are summarized in Table 1. The pellets are produced using a twin-screw pellet manufacturing device

(AIKI, ALM-LINE-KP), with each pellet being approximately 3 mm in size. Next, the tools are formed using a pellet-based 3D printer (S.lab, GEM200GDH), creating triangular cutting inserts with each side measuring 22 mm and a thickness of 5 mm. The parameters for this formation are detailed in Table 2. Additionally, tools with lattice structures of varying coarseness at volume ratios of 100%, 70%, 50%, and 30% are fabricated in four different types, with the 100% volume ratio being solid, devoid of any lattice structure. Following this, the formed tools are debound and sintered in a furnace. The debinding and sintering parameters are compiled in Table 3. A simplified diagram of the process, including pellet-based 3D printing, debinding, and sintering, is shown in Figure 1. Finally, the sintered tools are polished to sharpen the cutting edges, completing the finishing process.

Table 1. Raw materials and ratios in pellets

Material	WC	Co	PE	Pw	Sa
Mass ratio wt%	81	9	3.5	6	0.5

Table 2. 3D printing parameters

Nozzle diameter	Φ 1 mm
Nozzle temperature	180 °C
Bed temperature	60 °C/min
Extrusion rate (proportional to screw speed)	68% - 70%

Table 3. Sintering parameters

Degreasing hold time	2 hours
Degreasing temperature	450 °C
Rate of temperature increase to 450 °C	0.5 °C/min
Atmosphere for degreasing	Vacuum
Rate of temperature increase to sintering	6 °C/min
Sintering hold time	1 hour
Sintering temperature	1400 °C
Atmosphere for sintering	100% Argon
Pressure	2 kPa
Cooling rate	5 °C/min
Temperature at atmospheric exposure	300 °C

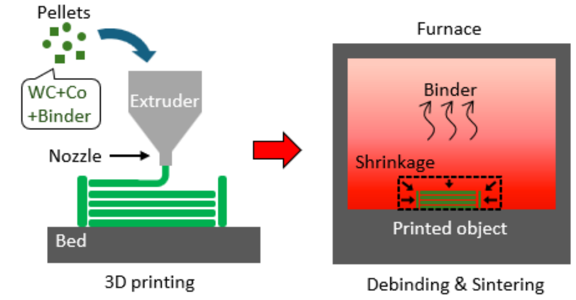

Figure 1. Process Flow of pellet-based 3D Printing, Debinding, and Sintering

2.2. Cross-section observation

To observe the microstructure of WC-Co cemented carbide tools fabricated through pellet-based 3D printing, cross-section observations are conducted. Initially, samples with cross-sections are created using wire electric discharge machining. These samples are then processed with Cross Section Polishing (CP) to prepare the surfaces for examination. The microstructures and voids within these samples are observed using a Scanning Electron Microscope (SEM) (JEOL, JSM-6510LA). Additionally, Energy-Dispersive X-ray (EDX) analysis is performed to examine elemental distribution. For comparison, tools manufactured through powder metallurgy are also evaluated in the same method.

2.3. Hardness evaluation experiments

To evaluate the hardness of WC-Co cemented carbide tools fabricated through pellet-based 3D printing, Vickers hardness (HV) is measured using a Vickers hardness tester (Shimadzu, HMV-G 21ST). Solid samples without lattice structures are used for the measurements. Due to variability in the measurement locations, multiple points are measured. For comparison, tools manufactured through powder metallurgy are evaluated using the same method as well.

2.4. Density evaluation experiments

To evaluate the density of WC-Co cemented carbide tools fabricated through pellet-based 3D printing, density is measured using an electronic densimeter (Alfa Mirage, EW-300SG). Measurements are taken for tools with lattice structures designed to have volume ratios of 100%, 70%, 50%, and 30% during the fabrication process. Water is deliberately permeated into the lattice to examine the condition of internal voids in the fabricated items. Additionally, density measurements are also conducted on WC-Co cemented carbide tools manufactured through powder metallurgy for comparison.

2.5. Cooling performance evaluation experiments

To demonstrate the cooling effect of the lattice structures in tools, cooling performance evaluation experiments are conducted on tools with differing coarseness of lattice structures at volume ratios of 100%, 70%, 50%, and 30%. Here, cooling performance refers to the ease with which the tool can be cooled by air or coolant during the actual cutting process. The experimental setup is as shown in Figure 2. The four types of tools are placed on a hotplate, and a blower is used to ensure that air flows evenly across the tools from one direction. The cooling process of the tools is then captured using thermography (Nippon Avionics, R500PRO) from the opposite side of the blower, comparing how lattice coarseness affects cooling efficiency. The temperature of the hotplate was set to 150 °C. To accurately measure temperatures, blackbody paint is applied to the tools.

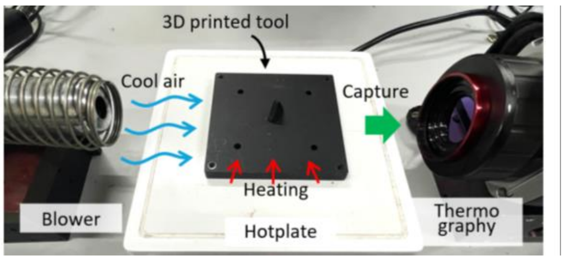

Figure 2. Setup for the cooling performance evaluation experiments

2.6. Cutting experiments

To demonstrate that WC-Co cemented carbide tools fabricated through pellet-based 3D printing can be utilized in actual cutting processes, turning process is performed using a conventional lathe (DMG MORI, LR-55A). The tools are of four different types, each with lattice structures of varying coarseness at volume ratios of 100%, 70%, 50%, and 30%, mounted in a specially designed tool holder. The workpiece is a 50 mm diameter round bar of S45C steel. In the turning process, the end face of the bar is cut from the outer edge to the center. The setup of the tools and the workpiece is shown in Figure 3. The parameters for turning are detailed in Table 4.

After the cutting experiments, the wear condition of the tools is observed using a laser microscope (Olympus, OLS4500). To evaluate the wear resistance of these tools, their wear conditions are compared with the tools manufactured through powder metallurgy, which were subjected to turning process under the same conditions.

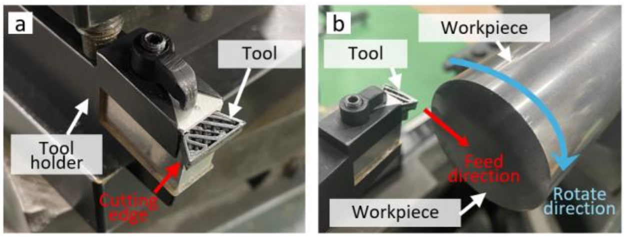

Figure 3. (a) Tool attachment (b) Experiments setup

Table 4. Turning process parameters

Spindle speed	855 rpm
Depth of cut	0.05 mm
Feed rate	0.08 mm/r
Number of end face turning cycles	20

3. Results and discussion

In this section, the results corresponding to the methods described in Section 2 are presented.

3.1. Tool fabrication

Using a pellet-based 3D printer, cutting inserts made of WC-Co cemented carbide with lattice structures of varying coarseness at volume ratios of 100%, 70%, 50%, and 30% were fabricated. Photos of the tools before and after sintering are shown in Figure 4. The linear shrinkage rate between pre-sintering and post-sintering was approximately 0.7 times, primarily caused by material densification as spaces between particles are reduced during the sintering process. After sintering and surface finishing through polishing, the dimensions of the tools were 15mm on each side and 3.5mm in thickness.

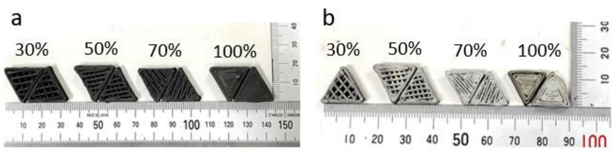

Figure 4. (a) Tool before sintering (b) Tool after sintering

3.2. Cross-section observation

Cross-sections of WC-Co cemented carbide tools fabricated using a pellet-based 3D printer and those made through powder metallurgy were examined using SEM / EDX. The images of these cross-sections are displayed in Figure 5. In the microstructure images (a and b), the whitish grains represent WC, and the darker areas are Co. While there are no significant overall differences, the powder metallurgy tools appear to have finer WC grains filling the gaps more densely, which could affect hardness. Observing a broader area (c, d and e), the tools made with the 3D printer revealed some voids and slight elemental segregation, which could affect density. The voids are likely related to the printing path used during the 3D printing process. As for the elemental segregation, it is thought to occur either during pellet mixing or during the melting and extrusion of the pellets. To achieve a more complete and defect-free structure, it is necessary to refine the fabricating parameters further.

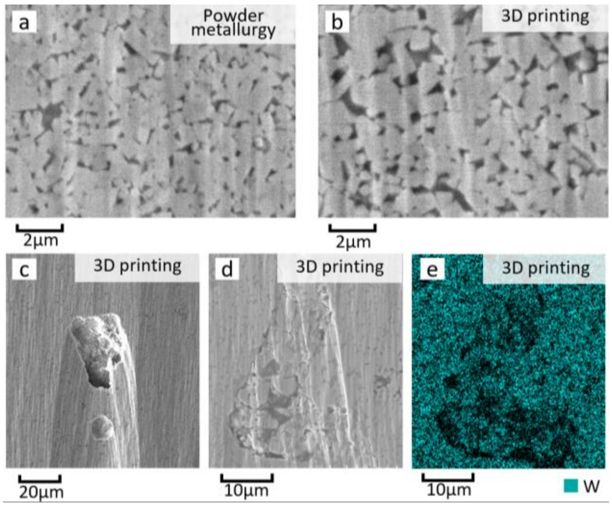

Figure 5. (a-b) Microstructure of tools: (a) powder metallurgy, (b) 3D printing; (c-e) Voids and elemental segregation of 3D printed tools: (c)voids, (d) elemental segregation, (e) elemental segregation analysed by EDX for the element tungsten

3.3. Hardness

The Vickers hardness of WC-Co cemented carbide tools fabricated using a pellet-based 3D printer and those manufactured through powder metallurgy was measured. The indentations made on each tool during the Vickers test and the graph of the measurement results are shown in Figure 6. The results indicate that although the hardness of the tools made through pellet-based 3D printing is approximately 10% lower, they still possess hardness levels comparable to those made by powder metallurgy. To achieve greater hardness, it is suggested that improvements in materials, fabrication, and sintering parameters are necessary to attain a denser structure.

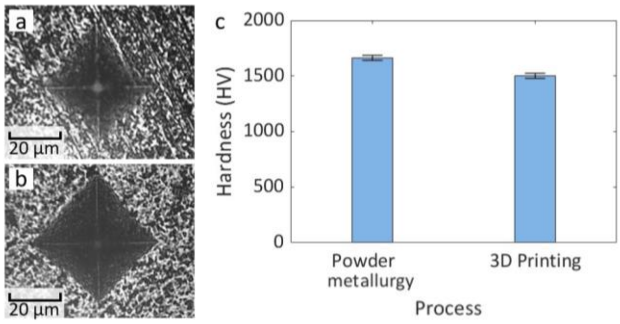

Figure 6. (a-b) Vickers hardness test indentations: (a) Powder metallurgy tool, (b) 3D printed tool; (c) Hardness comparison

3.4. Density

The density of WC-Co cemented carbide tools with lattice structures of varying coarseness at volume ratios of 100%, 70%, 50%, and 30%, fabricated using a pellet-based 3D printer, was measured and compared with tools manufactured through powder metallurgy. The results, as shown in Figure 7, indicate that tools produced by pellet-based 3D printing have densities up to 10% lower than those made by powder metallurgy, yet they still achieve sufficient density. This reduction in density is believed to be caused by internal voids. The observed trend of increasing density with coarser lattice structures can likely be attributed to the larger voids within the structure connecting to the exterior, reducing the occurrence of isolated voids. The density of the 30% lattice structure does not conform to this trend, which could be attributed to its being fabricated last, during which recycled pellets were used. This is thought to have introduced impurities and altered the proportion of components, leading to an increase in voids.

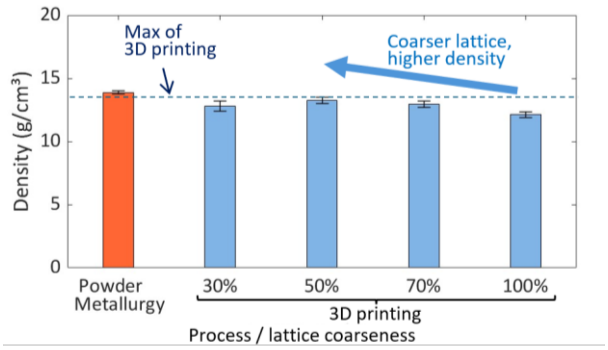

Figure 7. Density of powder metallurgy tools and 3D printed tools with varying lattice coarseness

3.5. Cooling Performance

Four types of WC-Co cemented carbide tools with lattice structures of varying coarseness at volume ratios of 100%, 70%, 50%, and 30% were placed on a hotplate, and cooled using a blower while being imaged with thermography. Before cooling with air, all tools started at a temperature nearly equal to that of the hotplate. Approximately 10 seconds after beginning the airflow, the tools reached the temperature distribution shown in Figure 8. At this point, the surface temperatures away from the heat source are approximately 100 °C for the 100% tool, 90 °C for the 70% tool, 80 °C for the 50% tool, and 60 °C for the 30% tool. From this result, the coarser the lattice, the more effectively the tool is cooled. This suggests that lattice structures significantly enhance cooling efficiency, which could be beneficial during the cutting process to prevent the tool from overheating.

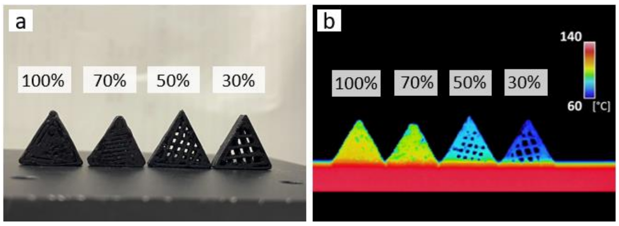

Figure 8. (a) Tool captured with a standard camera (b) Tool captured with thermography

3.6. Tool wear

WC-Co cemented carbide tools fabricated through pellet-based 3D printing were used for end face turning of S45C round bars. Results showed that all four types of tools, with lattice structures of varying coarseness at volume ratios of 100%, 70%, 50%, and 30%, successfully performed the cutting operation. The chip formation was of the flow type, suggesting that the machining process was stable.

Images showing the wear condition of tools after undergoing the same cutting process, comparing those fabricated through pellet-based 3D printing and those made by powder metallurgy, are shown in Figure 9. To compare the wear condition of tools after undergoing the same cutting process, the rake faces near the cutting edges of tools with a 100% fill fabricated through pellet-based 3D printing and tools manufactured through powder metallurgy were observed using a laser microscope. The images are shown in Figure 9. Using the laser microscope for height analysis, for the tool manufactured through powder metallurgy, a small wear approximately 3 µm deep was observed at the cutting edge, but no significant wear was detected elsewhere. In contrast, the tool fabricated through pellet-based 3D printing with a 100% fill exhibited wear approximately 5 µm deep. The principal areas of wear are highlighted with red frames in the images. Similar wear of approximately 5 µm deep was also observed for tools with other tools (70%, 50%, and 30%). These results suggest that tools fabricated through pellet-based 3D printing are slightly more prone to wear compared to those manufactured through powder metallurgy. The cause is believed to be due to the surface condition, particularly the presence of fine voids, and differences in the hardness. As observed in Section 3.2, micro voids exist in 3D printed tools, which may have triggered wear. Furthermore, the measurements in Section 3.3 suggest that 3D printed tools have slightly lower hardness, which may make them more susceptible to wear. To improve wear characteristics, it is considered necessary to optimize the manufacturing process to increase density and hardness.

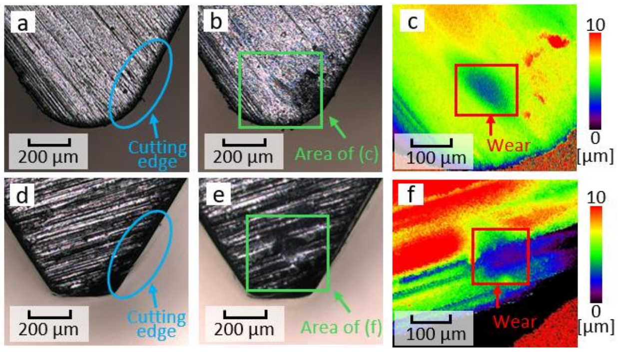

Figure 9. Rake faces near the cutting edges of tools: (a-c) powder metallurgy tool: (a) before cutting, (b) after cutting, (c) height profile after cutting; (d-f) 3D printed tool: (d) before cutting, (e) after cutting, (f) height profile after cutting

4. Conclusions

To enhance the cooling efficiency of WC-Co cemented carbide tools, tools with lattice structures were fabricated using a pellet-based 3D printing process. Hardness and density evaluation experiments revealed that WC-Co cemented carbide tools fabricated using pellet-based 3D printing nearly matched the mechanical strength of those made by conventional powder metallurgy. As a result of the cooling performance evaluation experiments, the lattice structures were found to greatly enhance cooling performance. Additionally, the cutting experiments verified that these tools are viable for actual machining operations.

As for the prospects of this study, in order to fabricate WC-Co cemented carbide samples with denser structures using pellet-based 3D printers, it will be necessary to optimize the proportions of raw materials, fabrication parameters, and sintering conditions.

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