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DEVELOPMENT ON DIAMOND TOOL WITH FORCED COOLING SYSTEM FOR HIGH SPEED CUTTING OF AERONAUTIC AND ASTRONAUTIC PARTS

Recently titanium alloys and nickel alloys have become eminent for making aeronautic and astronautic parts. Since both nickel alloys and titanium alloys have a very small thermal conductivity, the being used tool will suffer from a huge damage by heat generated during cutting process. Therefore, there is a requirement for a durable tool with excellent cooling capacity. In this research, a new electro-deposited diamond tool for high speed cutting of nickel alloys and titanium alloys was developed and evaluated. The new tool is a cup shaped end mill, its body is made from copper (due to its superior heat conduction characteristics) and the platting layer for bonding the diamond grains #120 is nickel. The cooling system is an advancement of the former used heat pipe. Water is supplied from outside through a thin tube, that is integrated in the tool body. Thereby the effect of water evaporation, featuring a very large cooling capacity, could be applied. The assayed materials were Ti6Al4V and Inconel 718. The cutting conditions were investigated by some pre-experiments. It is concluded from the results that; (1) The cooling capacity of the new tool using water evaporation is very effective to maintain the grinding potential of electro-deposited diamond tools, (2) The new tool is effective for high speed grinding of nickel alloys and titanium alloys (3) The new tool and compulsory cooling system are economical and eco-friendly.

1. INTRODUCTION

Recently titanium alloys and nickel alloys have become eminent for construction of aeronautic and astronautic parts, due to their high strength to weight ratio as well as their superior corrosion and thermal resistance. At this Ti6Al4V and Inconel 718 are the most widely used for titanium alloy and nickel alloy respectively. Cutting with low speed, high feed and a large depth of cut is recommended for a high chip removal rate, whereas high speed cutting with low depth of cut is recommended where high accuracy and excellent surface finish is needed as well as for machining with geometrical undefined cutting edges. [1] However profitable machining of titanium alloys or nickel alloys is a major production problem, as traditional deployed tools receive a huge damage by heat, plastic deformation

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and chemical reaction especially during high speed cutting because of the material properties of titanium alloys or nickel alloys. [2,3,4].

Therefore a strong tool with excellent cooling capacity is required. Cutting edges made of polycrystalline diamond (PCD) were assumed to be the optimal approach, as they combine distinguished strength and low chemical reactivity. Though it is crucial to keep the temperature of cutting point around 300°C to maintaine the cutting potential of PCD tools. [3],[5] In previous studies the cutting of cemented carbides with a electro deposited diamond tool was investigated. The cooling of tool was provided by the function of a heat pipe in the tool body. However, if titanium alloys or nickel alooys were machined by this tool, its cooling capacity was not sufficient for temperatures occuring during high speed cutting with a revolution of tool up to 50,000 rpm. [7]

For that reason, in this research a new cooling system for a electro deposited diamond tool was developed and its cooling capability for high speed cutting of Ti6Al4V and Inconel 718 was evaluated. The new approach is an advancement of the former investigated heat pipe tool. The form of body is a cup shaped end mill, and body material is copper. The cooling system is integrated in the tool body and the cooling medium is water. It is supplied from outside through a thin tube, and piped inside to the tip of tool where it evaporates. The emerging water vapor is channeled out through the tool and spindle. Afterwords the total cutting volume, tool temperature and tool life of the new tool, the heat pipe tool and a conventional electro deposited diamond tool were measured and compared to demonstrate the progressive productivity of the new approach.

2. EXPLANATION OF NEW APPROACH

2.1. PHYSICAL BACKGROUND

Titanium alloys like Ti6Al4V and nickel alloys like Inconel 718 are difficult to machine. This is manly caused by their physical and chemical characteristics. They have a very low thermal conductivity leading to strong head accumulation in the point of cutting. They also feature a high stiffness and toughness even at high temperature and tend to work hardening under influence of high cutting forces. Table 1 gives an overview over relevant material properties. In addition these alloys show a high chemical reativity with tool materials at temperatures over 500°C [8,9],[10].

As titanium alloys and nickel alloys have numerous applications in the aerospace and marine equipment industry as well as the medical industry, often a high accuracy and superior surface finish is demanded. Therefore high speed cutting is the operation to achieve requirements in practice. [1] But if tools for example made from cemented carbides are used a rapid tool wear associated with high costs has to be faced. The tool wear consists of mechanical deformation of the cutting edge, caused by the high modulus of elasticity and hardness featured by these alloys and damages caused by heat accumulation in the cutting area which leads to thermal deformation on the one hand and to chemical reactions between the chip-tool as well as the work piece-tool surface [3,4],[11].

Tools with cutting edges made of polycrystalline diamond offer mechanical properties that can particularly reduce tool wear caused by mechanical impact and chemical reactions with titanium alloy like chip adhesion. But diamond is susceptible to the influence of heat. Above temperatures over 300°C carbon diffuses out of the crystalline structure and a softening effect initiates as Fig. 1 shows [3],[5,6].

So it is essential that the focus of research is on an excellent cooling system to maintain an economical high speed cutting process for machining of these alloys. [12] But actually many traditional cooling liquids are being restricted due to environmental protection and high costs. One of the most cost effective and ecological friendly cooling medium is water. It furthermore owns the effect of evaporation under common circumstances. This phenomenon features a high heat transfer capability, shown in Fig. 2, as water absorbs a huge amount of latent energy while changing its state of aggregation [13].

2.2. EXPLANATION OF NEW TOOL AND COOLING SYSTEM

The form, shown in Fig. 3 (a), used for the new tool are similar to the former developed heat pipe tool. [7] The body is a cup shaped end mill, made from copper. The dimensions are 60 mm in length, 6 mm in outer diameter and 3.3 mm in inner diameter. The cutting edge consists of polycrystalline diamond grains SD #120 with a grain size

Table 1. Material properties of PCD and Ti6Al4V

Material property	Diamond (PCD)	Ti6Al4V	Inconel 718
Thermal conductivity [W/m·K]	2000	6.7	11.4
Modulus of elasticity [GPa]	700-1200	114	209
Hardness, Knoop	8000	392	414

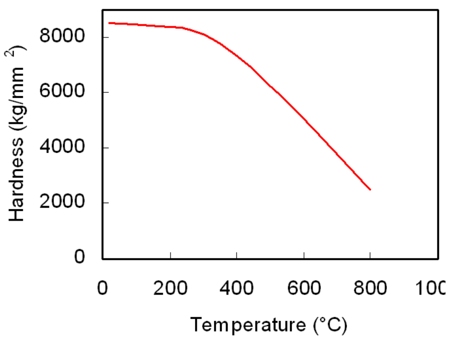


Fig. 1. Thermal softening of PCD

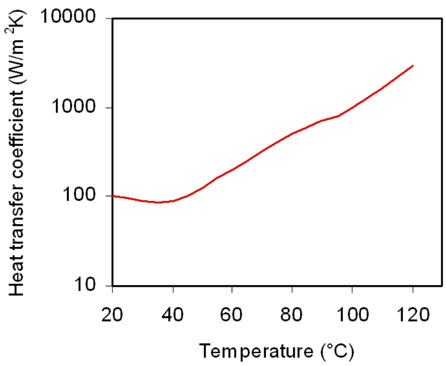
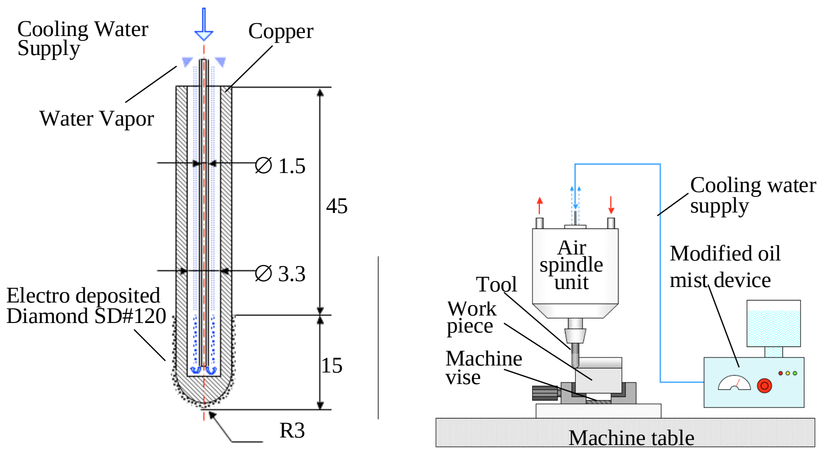


Fig. 2. Heat transfer coefficient of water

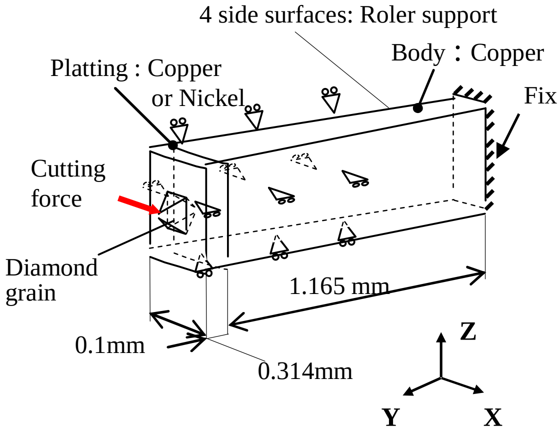
Fig. 1. Thermal softening of PCD Fig. 2. Heat transfer coefficient of water between 80 µm and 125 µm, bonded in a nickel layer. The length of the cutting edge is 15 mm.

The cooling system is integrated in the tool body. Cooling medium is water at room temperature. It is provided by a back up tank and supplied by a modified oil mist device over a thin tube, with an inner diameter of 1.5 mm, to the tip of the tool where it evaporates.



(a) New tool and cooling system (b) Machining set up

Fig. 3. Composition of new tool, cooling system and maching setup]



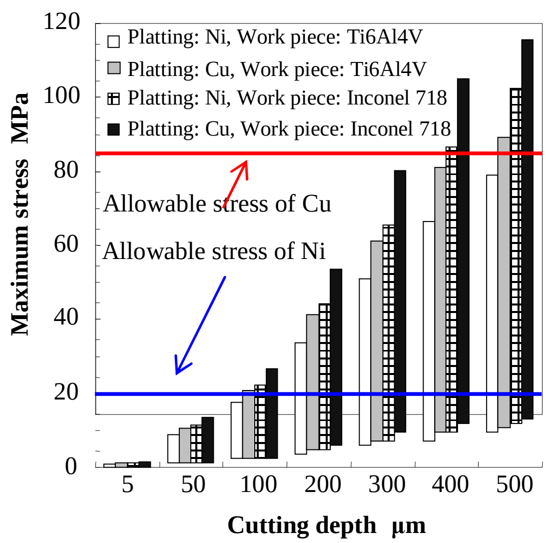


Fig. 4. FEM model for calculation ofmechanical strength regarding new electro-deposited diamond tool

Fig. 5. Calculation results of mechanical strength regarding new electro-deposided diamond tool

The emerging water vapor is drained off through the tool and exhausts through the spindle. The water volume is controlled and measured by the oil mist device. The machining setup is mapped in Fig. 3 (b). Then when copper was used for tool body, mechanical strength was investigated for machining data. FEM model regarding local of the tool is shown in Fig. 4. Bottom surface is fixed and 4 sides surfaces are supported along each surface (Roller support). Cutting force was loaded from side direction on the diamond grain. Relation between cutting depth and maximum stress (Von Mises) in the platting layer are shown in Fig. 5. If copper is used for the tool body, the tool can sufficiently cut about 50 μm depth. Copper platting had rather strong and large thermal conductivity than nickel platting. However as electro depositing of diamond grain using copper platting was difficult, we was nickel platting for the electro depositing of diamond grain. Thermal conductivity of Nickel is larger than one of the copper, however layer thickness is very thin, therefore that is no problem.

3. CUTTING OF TITANIUM AND NICKEL ALLOYS FOR EVALUATION

3.1. EXPLANATION FOR EVALUATION

Cutting property of both titanium and nickel alloys were investigated by using new diamond tool and its forced cooling system. Cutting condition and experimental view are shown in Table 2 and Fig. 6 respectively. The tool temperature is measured contactless by an infrared radiation thermometer as shown in Fig. 7. The method using thermocouples which is assumed to feature a higher accuracy cannot be deployed in this case, as the tool

Table 2. Grinding conditions for evaluation

Tool size	Φ6 mm × 60 mm length
Work pieces	Ti6Al4V: Hardness HRC 39, Specific grinding force 2470 MPa Inconel 718: Hardness HRC 36, Specific grinding force 3220 MPa
Work piece size	50 mm × 50 mm × 25 mm
Spindle speed	50000 min^{-1}
Grinding depth	1,2,3 μm
Feed speed	1250 mm/min
Contact length between tool and work piece	8 mm
Cutting distance	50 mm / 1 pass

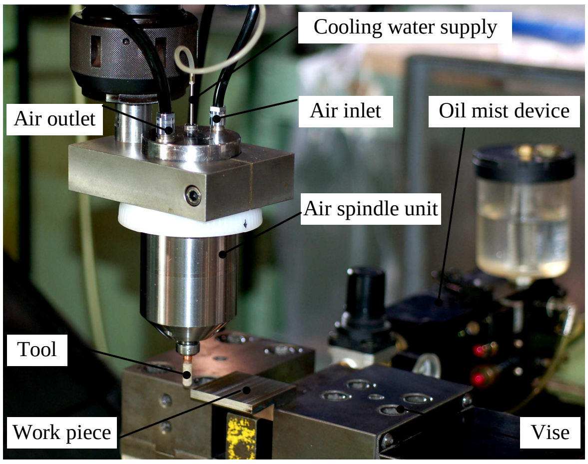


Fig. 6. Photogragh of the cutting system using new electro-deposited diamond tool and its forced cooling system

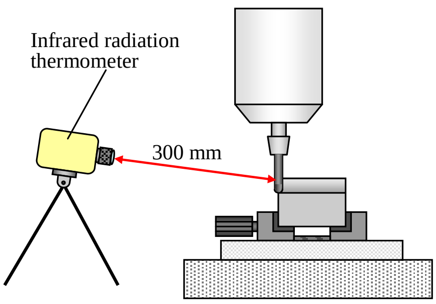


Fig. 7. Schematic view for measurement of tool temperature on the electro-deposited diamond too

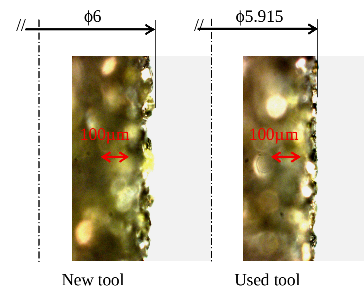


Fig. 8. Photograph of electro-deposited diamond of both pre-grinding and after grinding and the work piece with laser mark

rotates. Photograph of several diamond grain on the tool are shown in Fig. 8. When the edge condition changed from the left (= new tool) to the right (wear is 0.085mm), we judged that the tool life is finish.

3.2. RESULTS OF TOOL TEMPERATURE

Results for measurement of tool temperature are shown in Fig. 9. There are 4 kinds of cutting in the experiment; (1) Dry cutting using a conventional tool with solid body, (2) Heat pipe cooling with body made from SUS304, (3) New tool with body made from SUS304 and with new forced cooling system, and (4) New tool with body made from copper and with new forced cooling system. Ti6Al4V and Inconel 718 were used for work pieces, and cutting condition in Table 2 was used for the experiment. Results in Fig. 9 were tool temperatures when the cutting depth is 3.0 μm and cutting condition becomes at steady state. And water of 180 ml/h was supplied in the new forced cooling system. Cooling capacity of the new tool with its forced cooling system was 4 times of that of the conventional tool and 2 times of that of the heat pipe tool respectively. Cooling capacity of the new tool with its forced cooling system and body of copper was 1.5 times of that with body of SUS 304. The reasons are that generation heat on the diamond grain is effectively conducted to center of tool by copper body with large thermal conductivity and the conducted heat in the tool was effectively and directly cooled by water evaporation. Therefore the new tool with its forced cooling system and body of copper was very effective. Furthermore this forced cooling system is economical and eco-friendly because of using only water.

3.3. RESULTS OF TOOL LIFE

Results of tool life are shown in Fig. 10. Experimental parameters are similar to the pervious section.

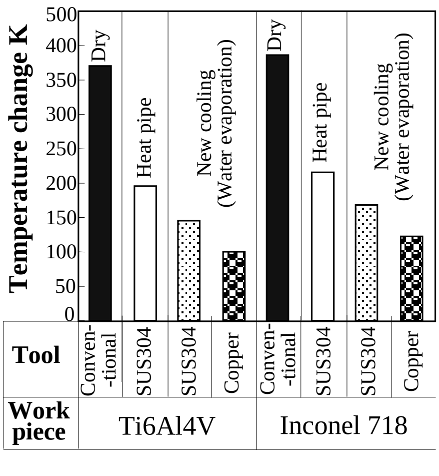


Fig. 9. Result of the temperature on the electro-deposited diamond tools

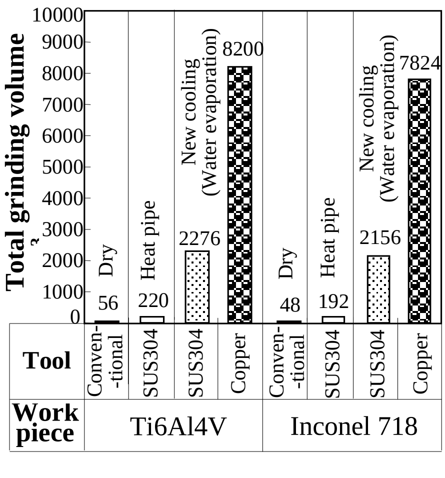


Fig. 10. Result of tool life test using several electro-deposited diamond tools

Tool life of the new tool with its forced cooling system was 146 times and 163 times of those of the conventional tool in Ti6Al4V and Inconel 718 respectively, and 40 times of that of the heat pipe tool. Tool life of the new tool with its forced cooling system and body of copper was 4.0 times of that with body of SUS 304. Titanium alloys and nickel alloys have a very low thermal conductivity and its cutting is very difficult because of large thermal load to the tool. However as the new tool with its forced cooling system and body of copper is excellent for countermeasure of thermal load, the tool life with this system was improved for cutting of low thermal conductivity.

3.4. RESULTS OF SURFACE ROUGHNESS

Surface roughness regarding the new tool and its forced cooling system was measured and evaluated. There are 2 kinds of cutting in the experiment; (1) Dry cutting using a conventional tool with solid body and (2) New tool with body made from copper and with new forced cooling system. Ti6Al4V and Inconel 718 were used for work pieces, and cutting condition in Table 2 was used for the experiment. In each experiment, cutting depth and water supplied for cooling are 1.0 μm and 120 ml/h, 2.0 μm and 150 ml/h and 3.0 μm and 150 ml/h respectively. Results of surface roughness are shown in Fig. 11. Surface roughness of the new tool with its forced cooling system was better than that of the conventional tool in both materials of Ti6Al4V and Inconel 718. We are thinking that hardness and other mechanical properties of grain on the tool were maintained at similar conditions of room temperature because of the excellent cooing system, and cutting resistance of new tool was smaller than that of the conventional tool.

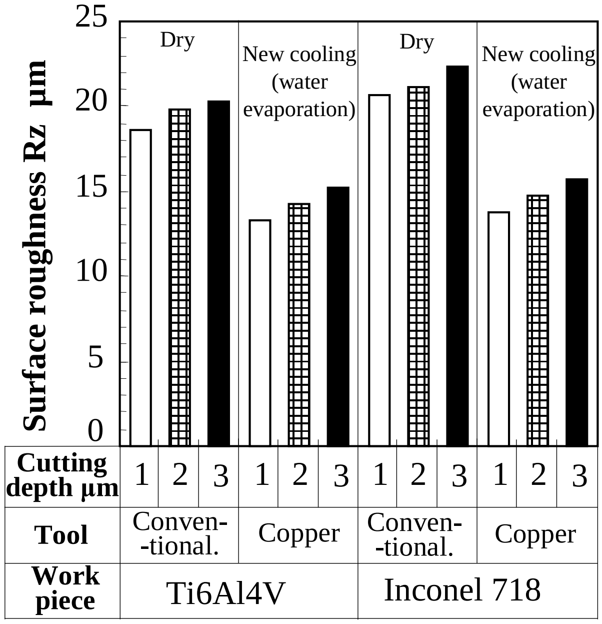


Fig. 11 Result of surface roughness using several electro-deposited diamond tools

4. CONCLUSIONS

The outstanding performance of the new approach in experiments is predominantly occurred from the distinguished cooling capacity using water evaporation, even though a conventional electro deposited diamond tool is not assumed to be suitable for dry high speed cutting of titanium alloy and nickel alloys. Similarly the approach using heat pipe cooling system meets its constraints, as it was designed to cut cemented carbides which feature decisive different material properties. It is concluded from the results that;

(1) The cooling capacity of the new approach using cooling with water evaporation is effective to maintaine the cutting potential of electro deposited diamond tools for high speed cutting of titanium alloy.

(2) The productivity of high speed machining of titanium alloys and nickel alloys can be considerable increased.

(3) The new approach and ecologically friendly.

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