

DESIGNING THE INTERNAL COOLING TURNING TOOL BASED ON NUMERICAL SIMULATION AND TAGUCHI OPTIMIZATION TECHNIQUE

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ABSTRACT

The paper presents the research content of applying numerical simulation to select the design option of turning tool with internal coolant line for machining SUS201 stainless steel. Heat transfer and CFD simulations for the insert are performed on Ansys with three design options: cooling grooves on the insert, cooling grooves on the tool holder and cooling holes in the insert to give the insert cooling results for each case. The simulation plan is carried out according to Taguchi design L_9 with 3 factors as cooling water flow rate, inlet cooling water temperature, insert cooling type and each factor has 3 levels. The simulation results determine the optimum coolant flow, optimum coolant inlet temperature along with the design of the cooling holes in the insert. Based on this design, an Internally Cooling Turning Tool (ICTT) is fabricated and used for experimental machining of SUS201 stainless steel. Experimental results of machining with ICTT show significant heat reduction effect on the tool insert and improvement of machined surface quality, reduced roughness compared to dry machining case.

Keywords: Internally Cooling Turning Tool (ICTT), numerical simulation, Taguchi optimization technique, Computational Fluid Dynamics (CFD).

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1. INTRODUCTION

Metal cutting with cutting tools accounts for a large proportion and plays an important role in mechanical processing. Metal cutting processes often generate a large amount of heat in the cutting zone, which has a negative impact on surface quality, machining accuracy, increases tool temperature, increases tool wear, and can affect the cutting ability of the tool. To remove heat from

the cutting zone and improve machining conditions, coolants are often used during metal cutting. However, this will lead to increased environmental pollution and increased processing costs. Minimum quantity lubrication (MQL) or dry machining is a current trend to minimize environmental pollution and reduce machining costs. Another solution that is also being researched and developed is to design and manufacture cutting tools with internal circulating coolant lines and use them in high-demand machining processes that do not cause pollution.

Stainless steel in general and SUS201 in particular are materials commonly used in the production of medical and food equipment that require high sterility.

These steels are difficult to machine with cutting tools because they have high ductility and high cutting heat generated during cutting, which often causes chip sticking and blade wear, affecting the quality, machining accuracy and tool life.

Stainless steel machining is often performed using tungsten carbide cutting tool under conditions of flushing with emulsion solution, thus increasing production costs as well as affecting the environment. Therefore, the solution of using cutting tools with internal circulating coolant in machining SUS201 steel is proposed in this study.

There have also been many studies on metal cutting with solutions to minimize the harmful effects of coolant solutions or using ICTT. A study [1] also proposed the solution of using cooling water when drilling holes in tempered 20XHM steel. This study showed that the roughness and the accuracy of machining holes when using cooling water are not much different than using oil or emulsion solution.

In [2], the author introduced a design of a turning tool with an internal coolant line. The research evaluated the influence of the cutting regime parameters (cutting speed, feed rate, depth of cut) on the cutting temperature in the insert and the machined surface roughness when turning A6061 aluminum in two cases of dry turning and turning by ICTT. When using ICTT the cutting temperature in the tool was reduced and the roughness was improved. In the thesis [3], the author proposes a novel ICTT. The results of CFD simulation and experimental studies of machining EN8 material and titanium alloy with this tool show significant heat reduction effect on the tool insert.

A new smart ICTT is presented in [4]. The internal cooling system of the cutting tool is controlled adaptively according to the temperature on the tool. The surface quality of 1040 steel was significantly improved when machining with the ICTT compared to dry machining with the same cutting parameters. Another ICTT with a design that allows coolant to be sprayed below the tool insert is presented in [5]. Experimental results of machining 1040 steel with this tool show a significant reduction in surface roughness compared to dry machining under the same cutting conditions.

A turning tool cooled by combining circulating internal cooling with spray cooling was presented in [6]. CFD simulations by ANSYS Fluent to optimize the cooling structure of the tool based on Taguchi method. The cooling efficiency of the tool was confirmed by experimental machining of 6061 aluminum alloy with the fabricated prototype of the tool. An ICTT using a mixture of water and ethylene glycol circulating in a PCBN tool is presented in the paper [7]. This tool was used for experimental machining of AISI D6 hardened steel. Experimental results showed that the cutting heat on the tool front was significantly reduced, the machined surface roughness and tool life were significantly improved compared to the roughness and tool life when machining dry with the same cutting parameters. A new ICTT design is also presented in the paper [8]. This tool was fabricated and tested on 304 stainless steels. Experimental studies showed that the tool life of ICTT was significantly improved compared to the tool life in dry machining and minimal lubrication machining with the same cutting parameters. In the review article synthesizing the research on ICTT [9], the authors have provided a literature review on the effectiveness and scope of ICTT application in turning machining. A

comprehensive review of internal cooling techniques for cutting tools and their effectiveness in the cutting process is presented in [10]. The effects of the internal cooling techniques on cutting temperature, cutting forces, surface roughness, and tool wear are summarized. Recommendations for applying these techniques are also given in the paper.

In general, the above studies mainly propose ICTT designs and use these tools in experimental research. There are almost no studies on selecting optimal ICTT design options. In this study, ICTT design options are analyzed and selected based on the application of numerical simulation tools and Taguchi optimization techniques.

2. OVERALL DESIGN

2.1. ICTT schematic diagram

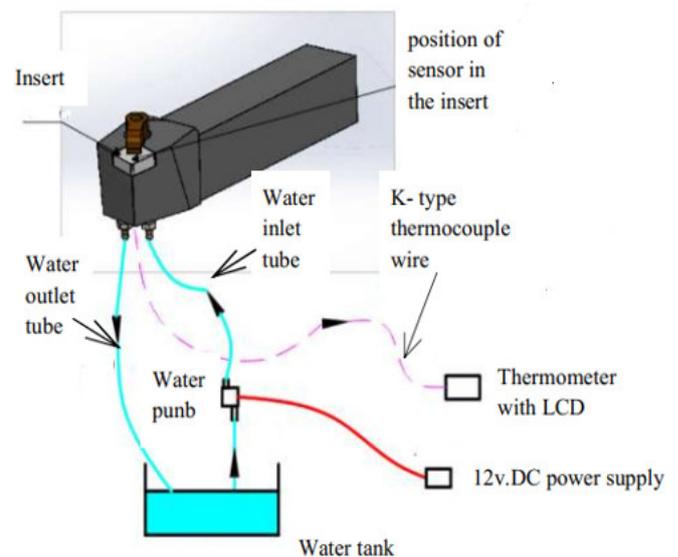


Figure 1. ICTT schematic diagram [2]

The cooling principal diagram of ICTT is shown on Fig. 1. The ICTT consists of three main components: turning tool, circulating cooling water system and tool temperature measurement system. The turning tool consists of a tool insert mounted on the tool holder by a clamping jaw and clamping screw. The tungsten carbide insert used for machining SUS201 stainless steel selected here has the symbol T3130 with the size of 12.7 x 12.7 x 3 (mm), rake angle 0° , clearance angle 15° from TUNGALOY. The insert is machined by EDM to create holes for thermocouples, holes or grooves for cooling water depending on the design as shown below. The tool holder is made of C45 steel according to the modified design, based on the ISO standard knife body symbol MSBNR2525M12 suitable for the designed tool insert. The

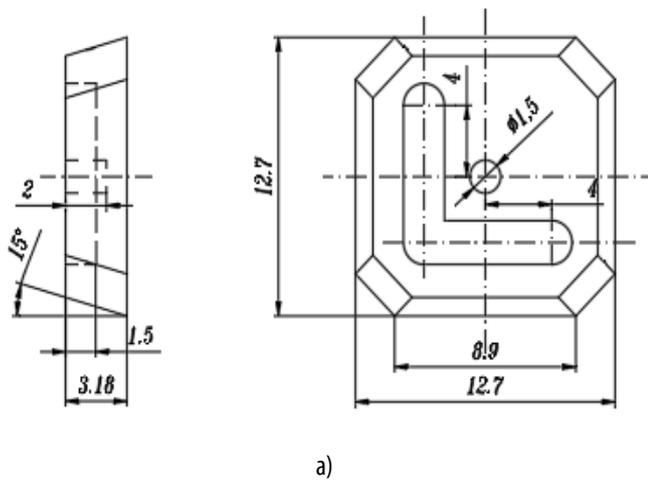
circulating cooling water system consists of water pump and 12VDC supply, inlet tube, outlet tube, and water tank. The tool temperature measurement system consists of thermocouple, thermometer with LCD.

2.2. ICTT design options

To solve the problem of reducing the cutting zone temperature including the cutting heat on the tool insert, three solutions have been proposed as follows:

Solution A - Design a cooling groove on the insert (Fig. 2). An L-shaped groove with a cross-sectional size of 2 x 1.5 (mm) is designed on the underside of the insert.

Water is circulated through the groove for cooling the insert. The tool holder has water supply inlet and drainage outlet for the insert.



- 1- Inlet hole
- 2- Outlet hole
- 3- hole for mounting thermocouple

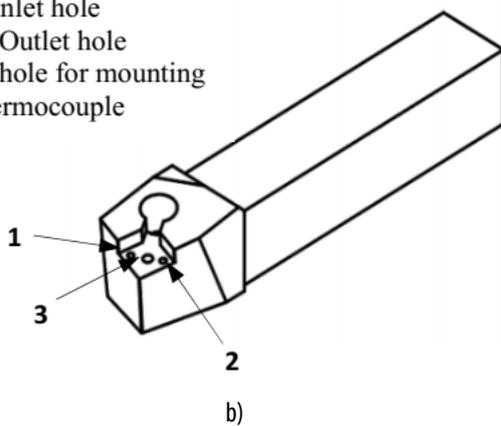


Figure 2. Solution A - L-shaped cooling channel on the tool insert
a- Tool insert; b- Tool holder

Solution B - Design a cooling groove on the tool holder (Fig. 3). An L-shaped groove with the same size as solution A is designed on the upper surface of the tool holder's insert cavity. Coolant is circulated through this groove to cool the insert.

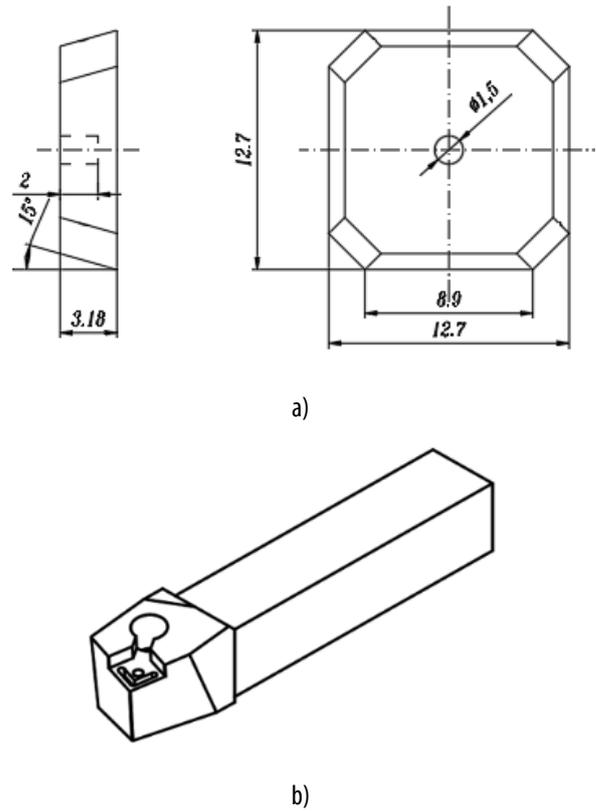


Figure 3. Solution B - L-shaped cooling channel on the tool holder
a- Tool insert; b- Tool holder

Solution C - Design the L-shaped cooling hole with diameter $\varnothing 2$ in the insert (Fig. 4). Water is circulated through this hole to cool the insert. The tool holder is the same as solution A.

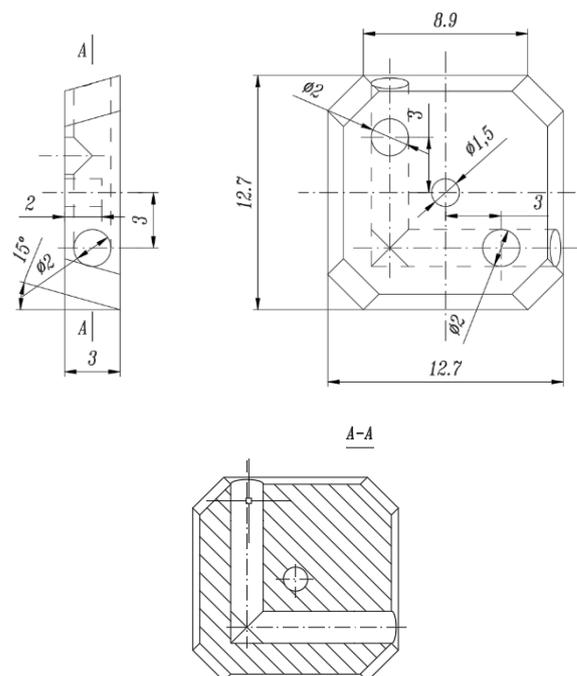


Figure 4. Solution C - Insert with internal L-shaped cooling channel

Structural analysis

The stresses in the insert are mainly caused by cutting force components. The pressure caused by the cooling water inside the cooling channel is negligible and should be ignored. The dimension of the contact area between the chip with the tool's rake is: 2mm × 1.5mm (refer from [3]). The cutting force components acting at the contact area are tangential force $P_z = 735N$, radial force $P_y = 240N$ and axial force $P_x = 728N$. These force components are determined from the empirical formula

$$P_{x,y,z} = 10 \cdot C_p \cdot t^x \cdot s^y \cdot V^n \cdot K_p \quad [11]$$

To evaluate the insert strength, the cutting regime chosen to be large with cutting depth $t = 2mm$, feed rate $s = 0.2$ (mm/rev), cutting speed $v = 150$ (m/min). Machining material is SUS201 steel; tool material is tungsten carbide.

Static structural simulation for the insert is conducted by ANSYS Workbench.

Simulation results of mechanical loads for three solutions are presented in Table 1.

Tungsten carbide has ultimate tensile strength as 344MPa, compressive strength as 1404MPa (Mat web). Therefore, the static strength of the insert with the coolant channel structure of all three options is sufficient.

Table 1. Simulation results of mechanical loads for three solutions

Solution \ Property	Maximum tensile stress (MPa)	Maximum compressive stress (MPa)	Total deformation (µm)
A- Cooling groove on the insert	249,75	131,59	2.826
B- Cooling groove on the tool holder	243,61	126,36	2.599
C- Cooling hole in the insert	220	133,5	2.796

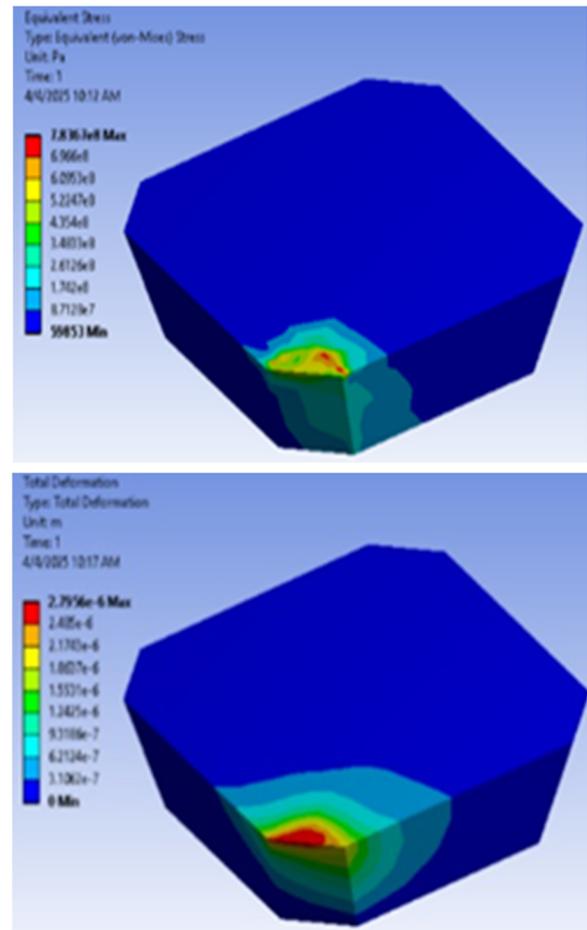
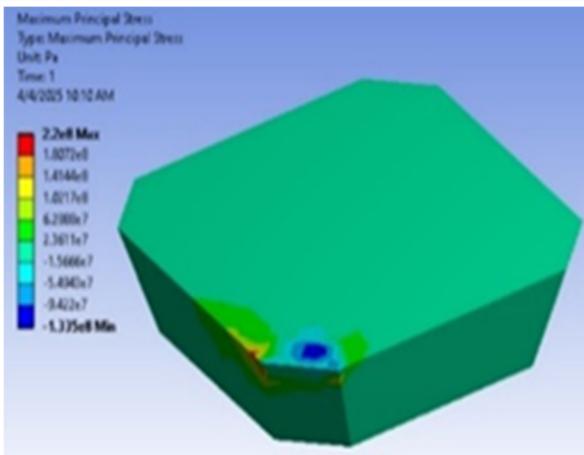


Figure 5. Static structural simulation for the insert with internal L-shaped cooling channel

3. DETERMINE OPTIMAL ICTT DESIGN SOLUTION

3.1. Theory basic

The Taguchi method proposes experimental matrices that help to carry out experiments with the least number of experiments. The optimal set of parameters is determined based on the S/N ratio of the output targets of the experiments as well as the levels of the input variables. The larger the S/N ratio, the more optimal the output targets. The S/N ratio is determined by the formula (1):

$$S/N = -10 \log_{10} (MSD) \quad (1)$$

With smaller is better:

$$MSD = \frac{y_1^2 + y_2^2 + y_3^2 + \dots + y_n^2}{n} \quad (2)$$

This method combined with variance analysis (ANOVA), also allows determining the level of influence of input factors on output targets.

CFD analysis is based on the finite volume method and numerical analyses are performed. The solution is

obtained by using general conversion equations for control of volume, mass, energy, etc. The conjugate heat transfer (CHT) model is also a CFD model which concentrates on conduction and convection heat transfer of the solid-liquid pairs in contact. The heat conduction equations are used for the solid domain, and the Navier-Stokes equations are used for the fluid domain., In this study, the CHT model is chosen for finite volume simulation analysis to obtain the temperature distribution results over the entire ICTT system. ANSYS FLUENT is used to simulate the temperature distribution and determine the maximum temperature on the tool.

3.2. Simulation setup

The purpose of the CFD simulation is to determine which insert design option will give the smallest insert temperature given a heat source applied to the chip-face contact area. Based on reference [3], the temperature in the contact area of the insert is set to 893.15K and the heat energy supplied to the tool is 125W. With a contact area of 2mm × 1.5mm, the heat flux will be 3880000W/m². Use this heat flux to simulate all three cooling water line design options. The remaining simulation parameters remain constant during the simulations, acting as boundary conditions as shown in Table 2.

Table 2. Boundary condition parameters

Parameter	Value	Parameter	Value
Velocity of water inlet V _{inlet} (mps)	2/3.5/5	Type of cooling	A/B/C
Temperature of water inlet T _{inlet} (°C)	15/20/25	Density of tool holder (kg/m ³)	8030
Density of insert (kg/m ³)	14900	Density of water (kg/m ³)	1000
Thermal conductivity of insert (W/m-K)	112.5	Thermal conductivity of Tool holder (W/m-K)	54
Specific heat of insert (J/kg-K)	208	Viscosity of water (kg/m-s)	0.001
Thermal conductivity of water (W/m-K)	0.6		

Table 3. Taguchi experiment plan and CFD simulation results

N ^o	V _{inlet} (m/s)	T _{inlet}		Type of cooling line	T _{tool} (°C)	
		(°C)	(°K)		(°C)	(°K)
1	2	15	288,15	A	253.05	526.2

2	2	20	293,15	B	304.85	578
3	2	25	298,15	C	255.75	528.9
4	3.5	15	288,15	B	291.15	564.3
5	3.5	20	293,15	C	235.05	508.2
6	3.5	25	298,15	A	247.65	520.8
7	5	15	288,15	C	221.25	494.4
8	5	20	293,15	A	233.95	507.1
9	5	25	298,15	B	296.75	569.9

The simulation calculation plan is designed according to the Taguchi experimental plan with 3 input variables: Coolant water speed (V_{inlet}), Coolant water temperature (T_{inlet}), ICTT design solution with levels presented in Table 3 The output target is the maximum temperature measured in the tool insert (T_{tool}) with the smaller is better option. The simulation calculation results are presented in the table, too.

Figure 6 shows the CFD simulation results for experiment 7 (V_{inlet} = 5m/s, T_{inlet} = 15°C (= 288.15K) & Cooling scheme C)

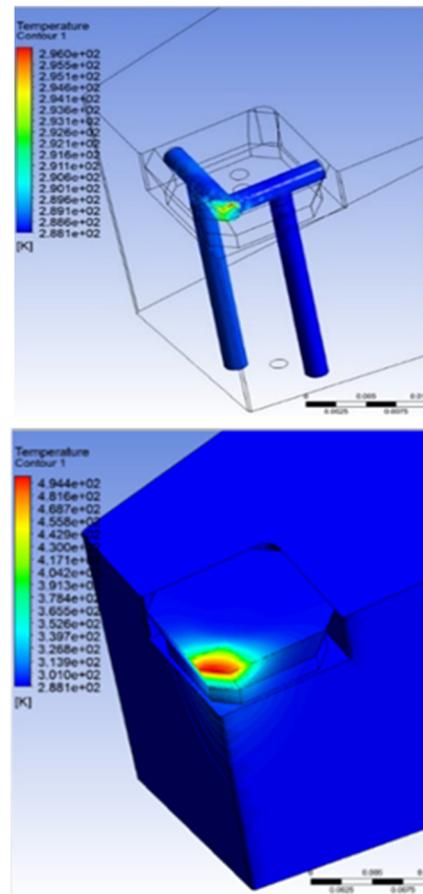


Figure 6. CFD simulation results for experiment no. 7 with cooling hole in the insert

3.3. Determine the optimal solution

The effects of V_{inlet} , T_{inlet} and Type of cooling line on the temperature at the tool are shown in Fig. 7. When the S/N is larger, T_{tool} is smaller. Through these graphs, it can be seen that the minimum temperature at the tool is achieved when $V_{inlet} = 5\text{m/sec}$, $T_{inlet} = 15^\circ$ Type of cooling line is C. Analysis of variance for S/N ratio of T_{tool} is presented in Table 4. By using ANOVA we have determined the influence of V_{inlet} , T_{inlet} and Type of cooling line on the temperature at the tool. The effect of coolant type on tool temperature was significantly higher (85.9%) than the effect of coolant velocity (10%) and the effect of coolant temperature (3.6%).

Table 4. Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Vinlet	2	0.7999	0.7999	0.3999	19.17	0.050
Tinlet	2	0.2862	0.2862	0.1431	6.86	0.127
Type	2	6.8699	6.8699	3.4349	164.6	0.006
Residual Error	2	0.0417	0.0417	0.0208		
Total	8			7.99781		

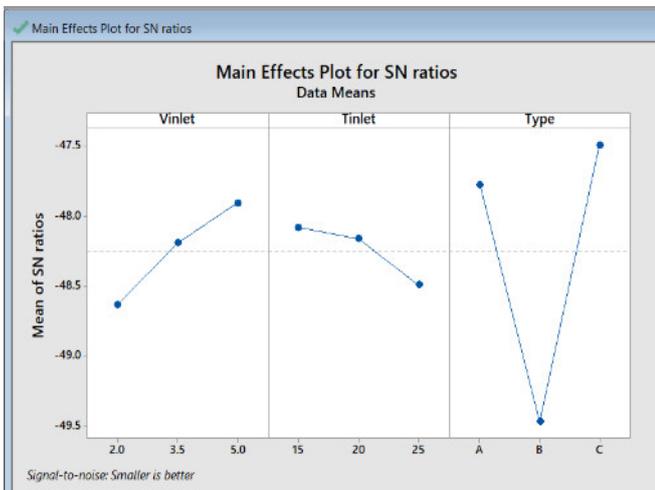


Figure 7. The effect of V_{inlet} , T_{inlet} and Type on the T_{tool}

4. MANUFACTURING THE ICTT AND EXPERIMENTAL MACHINING SUS201

The insert is EDM machined with a thermocouple hole and a cooling hole according to option C (Fig. 8a) and mounted on a tool holder manufactured according to the adjusted design (Fig. 8b). A temperature sensor is mounted on the tool to measure the maximum temperature rise across the insert (ΔT). This parameter is determined by measuring the maximum temperature in the insert during machining and the initial temperature of the insert. Cooling water with

temperature of 15°C is continuously supplied with $v = 5\text{m/s}$ through the inlet hole to cool the insert. The entire ICTT tool system was mounted on the CNC precision lathe model CPL-208 for trial machining (Fig. 8c).

SUS201 steel workpiece has size $\Phi 28 \times 200$ (mm). The cylindrical turning process was performed at a cutting speed of 75 m/min , feed rate of 0.07 mm/min , cutting depth of 0.3 mm . The experiments were conducted using three machining methods: dry machining, Flushing machining and machining with ICTT under the same cutting conditions. For each machining method, 3 sample bars were machined. The average values of temperature increase and roughness for each method are presented in Table 5 and Fig. 9. From this it can be seen that the roughness when using ICTT for turning SUS201 steel is reduced by about 26% compared to dry machining with the same cutting conditions. However, when using ICTT, the temperature on the tool insert is significantly reduced (78%) compared to dry machining. This not only improves the quality of the machined surface but also significantly increases the tool life.

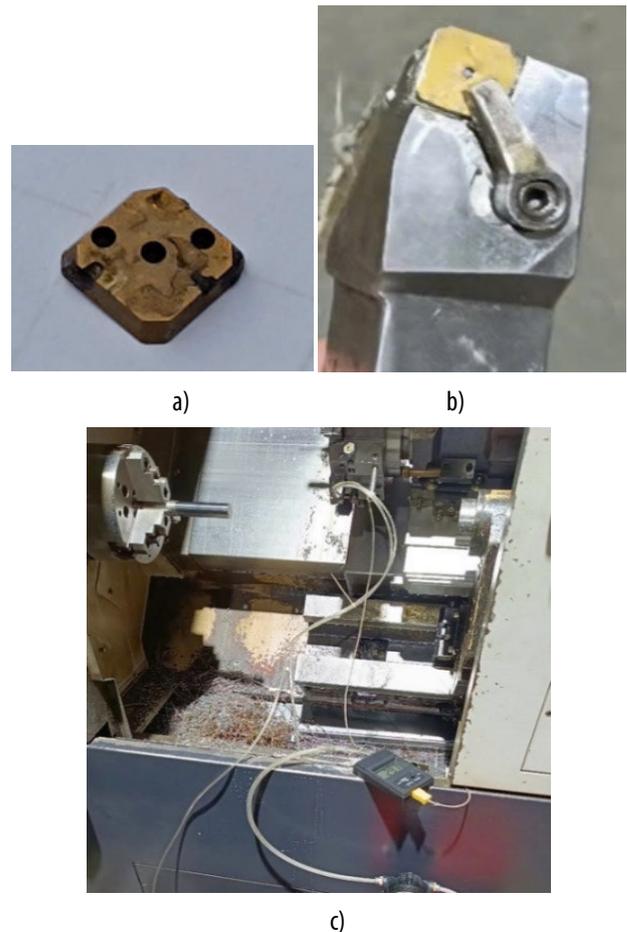


Figure 8. a- ICTT insert, b- ICTT insert and tool holder, c- Trial machining of SUS201 steel using ICTT

Table 5. Tool temperature and roughness for 3 machining types

Machining method	DeltaT (°C)	Ra (µm)
Dry cutting	51	1.046
Flushing	2.9	0.770
ICTT	11	0.907

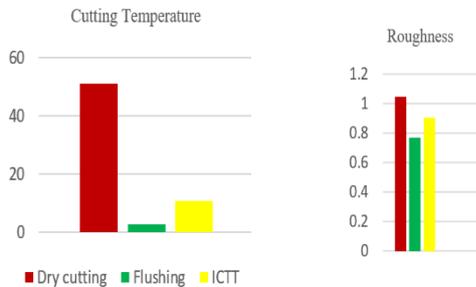


Figure 9. Comparison chart of tool temperature and roughness for 3 machining methods

5. CONCLUSIONS

The article introduces three ICTT design options for machining SUS201 stainless steel. Through numerical simulation with ANSYS and Taguchi method, the optimal input parameters to achieve the largest heat reduction on the insert were determined.

With the design of the cooling water line in the insert (option C), the cooling water speed of 5m/s, the inlet water temperature of 15°C, the tool insert temperature will be the lowest. An ICTT tool model with water line in the tool insert was fabricated and used for testing SUS201 machining steel. Experimental machining results using ICTT tool were compared with dry machining and machining with flooding. Initial experimental results show that the surface roughness when turning with ICTT is reduced compared to dry machining but still higher than that of machining with flooding. The temperature of the insert when machining with ICTT is also higher than when machining with flooding but is significantly reduced compared to when dry machining. This shows the prospect of applying ICTT to stainless steel machining of mechanical parts with high requirements on hygiene as well as contributing to green production without polluting the environment.

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