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STUDY ON MACHINING PROCESS OF MULTI-STEP HOLES BY USING THE STANDARD CUTTING TOOL AND STEPPED DRILL

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ABSTRACT

Besides technological solutions, machining productivity is a factor that it is always considered by manufacturers. The cutting tool (CT) is one of the key points to boost the cutting efficiency and improve machining productivity of the machining process. The proper cutting tool is a good solution for saving the cutting time, enhancing the machining quality, and improving the time life of machine tools. Traditional drilling method uses a standard cutting tool (SCT) with single cutting diameter that revealed disadvantages of low cutting velocity and high cost. This paper demonstrates a method of using the combination cutting tool (CCT)that equipped more cutting diameters in the same knife body to enhance machining productivity and reduce cutting time during drilling multi-step holes. By introducing a CCT, the machining productivity increases of about 131.72% and 257.9% in comparison to the CC in the option 1 and option 2, the cutting time deceases of about 72.06% and 56.85% in comparison to the CC in the option 1 and option 2, and the technology cost decreases of about 42.86% and 63.64% in comparison to the CC in the option 1 and option 2, respectively. The results show that the combination cutting tool is a good solution to improve the machining productivity and cost effectiveness during machining multi-step holes.

Keywords: *Machining process, cutting tool, cutting parameter, machine tool, multi-step holes*

1. Introduction

To meet marketing competition, manufacturers and engineers have been sought solutions to improve machining productivity such as applying ultrasonic technique for drilling to enhance machining performance and finishing surface (Moghaddas, Short, Wiley, Yi, & Graff, 2018), using tool condition monitor techniques of machine learning (ML) and internet of things (IoT) to improve productivity of CNC machining process (Kasiviswanathan et al., 2024), introducing water vapour to interface of cutter and workpiece to increase cutting speed and surface roughness of a high speed turning process (Kadam & Pawade, 2024), applying dry machining and hybrid dry machining methods to improve cutting productivity in machining metal (Pawanr & Gupta, 2024), using machine learning technique to enhance machining efficiency of the machining process (Rai et al., 2021; Soori et al., 2023), and using a cutting strategy of parallel spatial technique to enhance machining performance of milling thin wall part (Peng et al., 2025). There are many other concerns on the method and techniques to get high manufacturing performance of cutting time reduction, machining optimization, and productive feature such as improving turning productivity by using cooling technique (Sharma et al., 2009), enhancing productivity for micro-drilling by assistance of ultrasonic vibration (Ullah et al., 2025), applying monitoring technique of tool condition to improve machining performance of cutting process (Kuntoğlu et al., 2021; Mohamed et al., 2022; Pimenov et al., 2023), using high pressure of cooling fluid to enhance the machining productivity during machining process of Ti-6Al-4V material (Zaman & Dhar, 2024), developing a new tool of three-pads to enhance the productivity for machining the deep hole (Li et al., 2025). Some other methods can be applied to improve machining performance such as selecting advanced machining methods (Machado et al., 2024), machining on multi-axis machines (Pessoles et al., 2013), optimization of cutting condition (Gimadeev et al., 2025; Minquiz et al., 2020), optimizing toolpaths (Woo et al., 2022), and simultaneously processing by tool with multiple cutting edges and combined cutting tools (Mikolajczyk et al., 2019; Shi & Ning, 2025).

Cutting tool (CT) is really important in machining process of the mechanical products for many practical applications such as machined parts (Szczotkarz et al., 2021), gear (Hodgyai et al., 2024), automobile parts (Özbek et al., 2021), aerospace parts (Adin, 2024; Singh et al., 2024), and so on. During machining process, the cutting tool moves following the predetermined toolpaths to remove chips out of the workpiece to get the required product (Abellán-Nebot et al., 2024; Karpuschewski et al., 2021). There are some criteria that impact on the cutting behavior of the cutting tool such as material (Grigoriev et al., 2021), the shape of the cutting tool, the structure of the CT (Navaneethan et al., 2024). The system of cutting tools for processing hole has been standardized and diversified in structure, which makes it easy for technologists to choose cutting tools that are suitable for technological solutions when processing on automatic machines (M. Chen et al., 2007). However, it is difficult to select a good cutting tool for getting high machining performance such as drilling a multi-step holes. Combined tool has been used in drilling operations with good characteristics reduction of machining cost and operation time (Kamble et al., 2020; Krebs et al., 2025). The choice of machining method to improve the machining productivity that depends on the technological characteristics of each type of surface requirement and manufacturing quantity. Therefore, it is very necessary to study the machining productivity, cutting ability, and durability of cutting tools with many cutting edges participating simultaneously in the cutting process; contribution to mastering the manufacturing technology of cutting tool, improving the competitiveness of products, and completing the processing technology (Sokolova et al., 2021). In fact, many machine parts have step holes (one or two steps) to assemble the bolts that link the machine parts together. With traditional method, the step holes are machined with conventional cutting tools. The technological process must be done through the following steps: drilling center, drilling, boring, and chamfering. However, with using the combined cutting tools (CCT), the above technological process will be completed in one technological step. This paper demonstrates a method of using the combination cutting tool (CCT)that equipped more cutting diameters in the same knife body to enhance machining productivity and reduce cutting time during drilling multi-step holes. The wok has used calculation, analysis and graphing methods to investigate the productivity limitations when machining multi-step holes by the standard cutting tools in comparison with the combined cutting tools. The combination cutting tools are designed for machining multi-step holes, specifically for a specific technological process, and at the same time. Standard cutting tool (SCT) and combination cutting tool (CCT) are the tools that technologists normally use to machine the holes on the hard materials such as steel and wood. The article has used calculation, analysis and graphing methods to investigate the productivity limitations when machining multi-step holes by the standard cutting tools in comparison with the combined cutting tools. The combination cutting tools are designed for machining multi-step holes, specifically for a specific technological process, and at the same time. The paper studies on the issue of productivity and machinability with a combination tool compared to a standard cutting tool. By introducing a CCT, the machining productivity increases of about 131.72% and 257.9% in comparison to the CC in the option 1 and option 2, the cutting time deceases of about 72.06% and 56.85% in comparison to the CC in the option 1 and option 2, and the technology cost decreases of about 42.86% and 63.64% in comparison to the CC in the option 1 and option 2, respectively. The results show that the combination cutting tool is a good solution to improve the machining productivity and cost effectiveness during machining multi-step holes.

2. Materials and Methods

The workpiece material is aluminum (A6061) that used in the investigating the machining productivity and cutting time during machining process with SCT and CCT cutters. The machining operations were conducted on a CNC machine tool. The machining operations include milling and drilling operations. The machining feature is a step hole with different diameters and depths that lied on the same centerline.

When machining step holes with the same centerline position, the technologist usually selects a standard cutting tool (SCT), encodes the position, and installs it in the tool library. The machining program will call each tool in turn for machining according to the technological process as: (1) Using a center drill to locate the hole coordinate; (2) Using a standard drill to make base hole; (3) Chamfering with a chamfering tool; (4) Using a milling tool to make a step hole; (5) Finishing the hole with a reamer; (6) Tapping with a thread tool (C.-S. Lee et al., 2013; Mironova & Kondratenko, 2019; Qudeiri et al., 2006). The cutting parameters are calculated by following equations (B. Y. Lee et al., 1998; Othmani et al., 2008; Tolouei-Rad & Bidhendi, 1997):

The cutting speed is calculated as following equation (1):

$$V_c = \frac{\pi D n}{1000} (mm / \min) \tag{1}$$

The machining time is calculated as following formula (2):

$$t = \frac{L_d}{n F_r} \tag{2}$$

Where:

V_c is the cutting speed (mm/min); D is tool diameter (mm); n is the spindle speed (rev/min); F_r is the feed rate (mm/rev); t is the cutting time (min); L_d is the depth of cut (mm).

The time required to complete a technological step is calculated by the following formula:

$$t_{b(i)} = t_{d(i)} + t_{cn(i)} \tag{3}$$

Where $t_{d(i)}$ is the tool change time that depends on manufacturer ($t_{d(i)}$ as constant); i is the ith processing step; $t_{cn(i)}$ is the processing time.

The total manufacturing time is calculated as following equation (4):

$$t_{\Sigma} = \sum_{i=1}^{m} t_{b(i)} \tag{4}$$

Where m – number of processing steps.

The machining stroke length (L_i) is calculated by the following formula (5):

$$L_i = L_{oi} + L_{di} + L_{1i} \tag{5}$$

Where L_{oi} is the safe distance of cutting tool; L_{di} is the depth of the hole; L_{1i} is The retract distance

The safe distance of the tool position before machining is often chosen as L_{0i} of about 10 mm. It ensures that non-collision will be occurred between the cutting tool and the workpiece during the cutting process. To drill through the depth of the hole, the additional feed length is chosen as L_{1i} of about from 15 mm to 20 mm.

Besides the above-mentioned SCT machining methods, technologists can also choose the method of using combination cutting tools (CCT), in which the cutting positions are manufactured in a monolithic or assembled manner. The technological process of machining different surfaces of the hole system is carried out on the same movement of the tool as shown in **Fig. 1**. Base on the technological process of multi-step hole machining using the two technological methods mentioned above, it can be seen the difference in productivity/processing time. The machining method using standard cutting tools will give lower machining productivity due to the stopping time to change the tool, the time to move the cutting tool before, during and after each technological step. By using a combination cutting tool, the tool will only be changed once time and the part will be completely machined on the same cutting stroke.

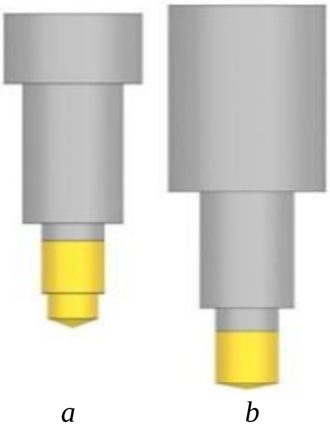

Fig. 1. The images of a combination machining tool consisting of two cutting edges: a - The combined machining tool including a hole drill with diameter of Φ9.5 mm and a milling cutter with a cutting edge on the end face for machining stepped holes with diameter of Φ14.5 mm; b - The combined machining tool includes a hole drill with a diameter of Φ14.5 mm and a boring tool with a 45-degree inclined cutting edge for chamfering a hole diameter of Φ20.5 mm and a shaping boring bit with a diameter of Φ20.5 for machining a hole diameter of Φ20.5 mm.

3. Results and discussion

There are many research groups focused on investigating the cutting performance of the cutting tool during machining process such as building method of selecting tool material for machining process (Niu et al., 2020), using digital twin model to control the cutting tool for enhancing productivity (Xie et al., 2021), investigating the effect of heat on the cutting behavior of the cutting tool during machining process (Hao & Liu, 2020), improving sustainability of cutting tool via using life prediction technique (Sun et al., 2020), using a modification technique for cutting tool features of flank and rake faces to improve cutting performance (Y. Chen et al., 2019), using diamond coating technique for cutting tool to machine difficult-to-cut materials and improve cutting performance (Akgün & Kara, 2021; Derakhshandeh et al., 2023; Xin et al., 2022; J. Zhang et al., 2024), building a selection method of cutting tool for metal machining process (Duan et al., 2021), getting high cutting performance of cutting tool via selection technique of the cutting tool during machining aluminum material (Pattnaik et al., 2018), applying fuzzy model to manage the heating that effects on the cutting tool during manufacturing on the CNC machine tool (Bobyr et al., 2020), investigating the effect of microstructure of the cutting tool on the cutting performance during turning process (Fouathiya et al., 2021), developing automatic method of detecting breakage behavior of cutting tool during machining process (Xiao et al., 2022), getting machining stability of cutting process via using hybrid prediction model of simulation data and measurement data (N. Zhang et al., 2024), and using a deep learning model to predict the cutting tool life for improving the production quality and productivity of machining process (Zhang et al., 2021). However, it is still lack deep investigating on the benefits of using combination tool during machining multi-step holes. The survey was carried out on a workpiece material of aluminum (A6061). The material has high durability and high productivity. It is used for processing electronic jigs, molds, manufacturing machine parts – automation, especially in the field of manufacturing smartphone devices. The machined part has the hole surfaces that need to be machined as shown in **Fig. 2.** The processing time is calculated with the two options for choosing standard cutting tools and specialized tools. **Table 1** shows the detail dimensions of the multi-step holes.

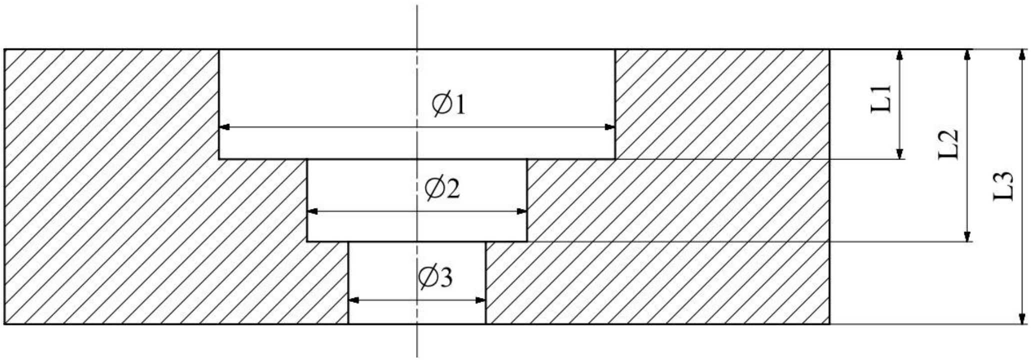

Fig. 2. Detail drawing of three-stepped hole for machining

Table 1 - Machining features

Feature	Diameter (mm)	Length (mm)
1	22	20
2	16	40
3	10	60

Based on the analysis of the above processing methods, the following options can be applied to process the details as shown in **Fig. 3**.

Option 1: Use a standard shaping cutter

Processing the hole surfaces as shown in **Fig. 2** must go through 4 technological steps with 4 tool changes, the order of technological steps is as shown in **Fig. 3** with: Step 1 (Center drilling); Step 2 (Drilling holes with a Φ10 cutter); Step 3 (Milling step holes with a Φ22 cutter); and Step 4: (Milling step holes with a Φ16 cutter).

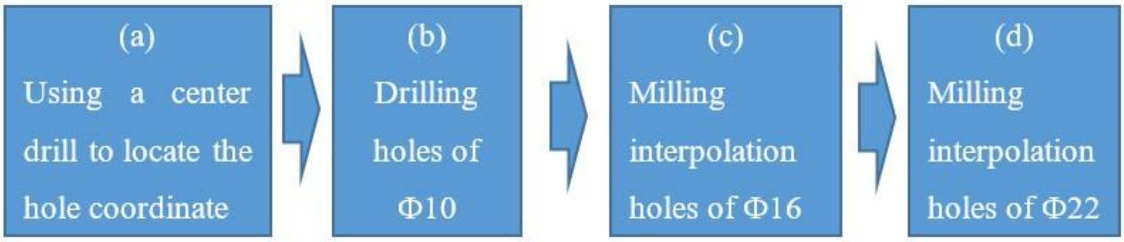

Fig. 3. Sequence of hole machining steps using standard shaped cutting tools: a - Center drilling; b - Drilling holes of Φ10; c - Milling interpolation holes of Φ16; d - Milling interpolation holes of Φ22

Option 2: Using standard cutting tools

To machine hole surfaces as shown in **Fig. 2**, it is necessary to go through 4 technological steps with three tool changes, the order of technological steps is as shown in **Fig. 4** with: Step 1(Center drilling); Step 2 (Drilling holes with Φ10 cutter); Step 3 (Milling interpolation holes of Φ16 degree with Φ10 end mill); and Step 4 (Milling interpolation holes of Φ22 degree with Φ10 end mill).

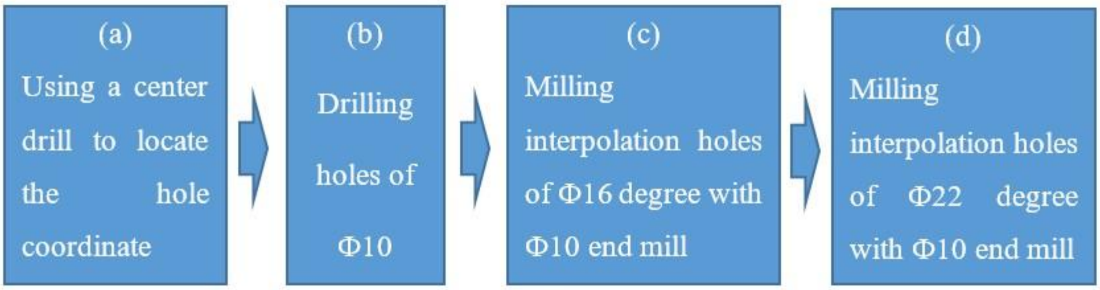

Fig. 4. Sequence of steps for machining holes with standard cutting tools: a - Center drilling; b - Drilling holes of Φ10; c - Milling holes of Φ16; d - Milling holes of Φ22

The time for interpolating round holes Φ16 and Φ22 with a Φ10 cutter is calculated by the following formula (6).

$$t_p = \frac{60ml}{nF}. \qquad (6)$$

Where:

t_p is the milling time (s); L is the cutting stroke length (mm); F is the feed rate (mm/rev); m is the number of the cuts.

Number of cuts (m) when machining holes of steps Φ16 and Φ22 with end mill Φ10 that is calculated by following equation:

$$m = \frac{Depth\_of\_hole}{Depth\_of\_cut} = \frac{20}{5} = 4.$$

The interpolated lengths of circles Φ16 and Φ22 are calculated as below:

$$L_{\varnothing 16} = \pi(\varnothing 16 - \frac{D}{2}) = 3.14(16-5) = 34.54(mm).$$

$$L_{\varnothing 22} = \pi(\varnothing 22 - \frac{D}{2}) = 3.14(22-5) = 53.18(mm).$$

Option 3: Using a specialized cutting tool

To process the surface as shown in the drawing, only one technological step is needed on the same cutting stroke by a combination cutting tool as shown in **Fig. 5**. Based on formulas (1) to (6) and the cutting mode handbook when machining aluminum, it can be established a table of cutting mode parameters corresponding to the machining methods as shown in **Table 2**.

Fig. 5. Hole machining with combination cutting tool

Table 2 - Time required to machine the surfaces of the part according to three options

Option 1: Using standard shaping cutter					
Processing step	n (rev/min)	f (mm/min)	l (mm)	td (min)	tb(i) (min)
Step 1	500	0.5	30	0.05	0.080
Step 2	200	0.6	85	0.05	0.305
Step 3	300	0.7	30	0.05	0.120
Step 4	300	0.7	50	0.05	0.167
Total times					0.672
Option 2: Using standard cutting tools					
Processing step	n (rev/min)	f (mm/min)	l (mm)	td (min)	tb(i) (min)
Step 1	500	0.5	30	0.05	0.080
Step 2	200	0.6	85	0.05	0.305

Step 3	800	1.2	243.52	0.05	0.415
Step 4	800	1.2	158.16	0.05	0.237
Total times					1.038
Option 3: Using a specialized cutting tool					
Processing step	n (rev/min)	f (mm/min)	l (mm)	td (min)	tb(i) (min)
Step 1	280	0.6	110	0.05	0.29
Total times					0.29

Fig. 6 shows the machining time chart for three cutting selection options with the highest time belonging to the second option.

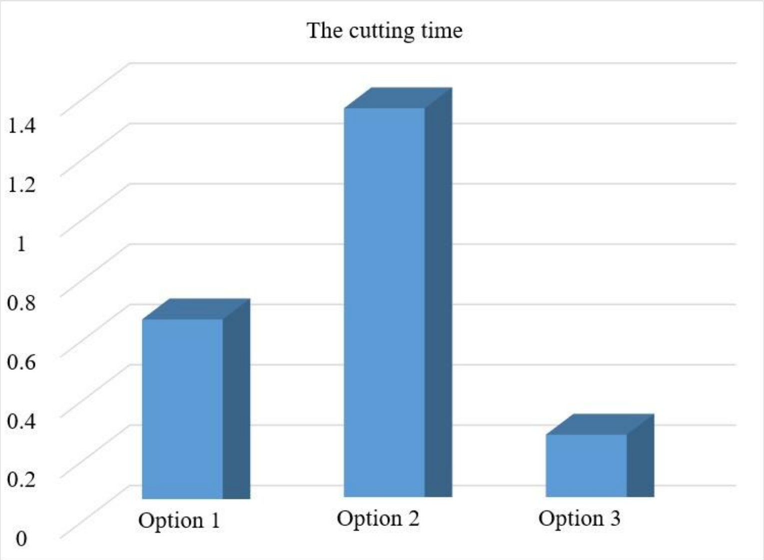

Fig. 6. Time chart when machining with 3 options different cutting tools

Fig. 6 shows that the time to complete the machining of the part with standard tools is much higher than with combination tools, the reason is due to the time to stop changing the tool, the time to move without cutting and repeat the machining distance many times with many cutting slices.

Let (T) be the cost of production (including the cost of machine shifts and fixtures), then the production cost function is determined by the following formula:

$$T = T_m + T_f + \sum_{k=1}^{i} T_{tk}. \qquad (7)$$

Where T_m is the machine depreciation cost; T_f is the cost of making fixture; T_{tk} is the cost of cutting tool of k^{th}

Let Q be the machining productivity), corresponding to each technological solution mentioned above will create the corresponding machining productivity Qi (product/hour). If choosing the standard cutting mode (V_c as a constant) in the technological solutions, the cost of cutting tools will depend mainly on the machining productivity, then the productivity and cost are shown in **Table 3**.

Table 3 - Processing cost according to 3 options

No	Cutting time (min)	Manufacturing tool cost coefficient	Machine depreciation cost Tm (Dollars/hour)	Cost of cutting tool Tdc (Dollars/hour)	machining productivity Qi (product/hour)	Technology cost

Option 1	0.672	1	47.21	0.39×10^{-2}	714.3	0.07
Option 2	1.038	1	47.21	0.39×10^{-2}	462.4	0.11
Option 3	0.29	2	47.21	0.79×10^{-2}	1655.2	0.04

From the calculation results in **Table 3**, it can be constructed a graph of the relationship between processing productivity and technological cost corresponding to three technological options as shown in **Fig. 7**.

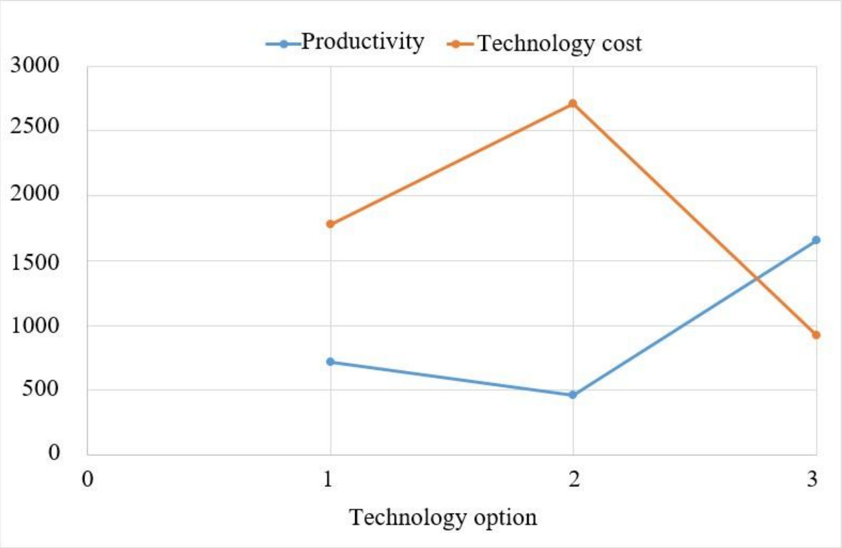

Fig. 7. Graph of the relationship between productivity and technology cost

From **Table 3** and **Fig. 7**, it can be seen that option 2 is 0.11 dollars. The technology cost is very high, and the productivity is very low. So, it is difficult to apply in mass production. Thus, option 1 and option 3 are two feasible options that can be applied, however, in reality, the choice of a specific option depends on the production output demand, so it is necessary to survey the balance point of production output, cost and production output.

The process of finding the balance point of productivity, cost and production output is to build a mathematical relationship between the production cost target function (T), the productivity target function Qn and the desired production output Qs, the parameters are shown in **Table 4** (Ahmed Al-Dujaili, 2013; Heshmati, 2003; Rawat, Gupta, & Juneja, 2018).

Table 4 - Relationship between cost, productivity and yield

No	Option 1	Option 3
T (price)	T1	T3
Ns (productivity)	Ns1	Ns3
Qn (yield)	Qn1	Qn3

Equation of the demand function for output:

$$T_s = a + bN; (b < 0) \quad (8)$$

With two technological options, it can be built a system of equations for the demand function of the output (9).

$$\begin{cases} T_{s1} = a + bN_1; \\ T_{s3} = a + bN_3. \end{cases} \quad (9)$$

Solving the system of equations (9), it can be got the output demand function equation (10):

$$T_s = a - bN. \qquad (10)$$

Equation of demand function for productivity:

$$T_n = c + dQ_n; (c > 0). \qquad (11)$$

With two options, it can be built a system of equations for productivity demand:

$$\begin{cases} T_{n1} = a_1 + b_1 Q_1; \\ T_{n3} = a_3 + b_3 Q_3. \end{cases} \qquad (12)$$

Solving the system of equations (12), it will have the equation of the productivity demand function as below:

$$T_n = c + dQ. \qquad (13)$$

The equilibrium point is the point at which a level of demand for output is appropriate to the production capacity that can meet it. At the equilibrium point, it can get the optimal price for manufacturing the combined processing tool to increase the competitiveness of the product in the market. The determination of the equilibrium point is applied by analytical methods or graphical methods as shown in **Fig. 8.**

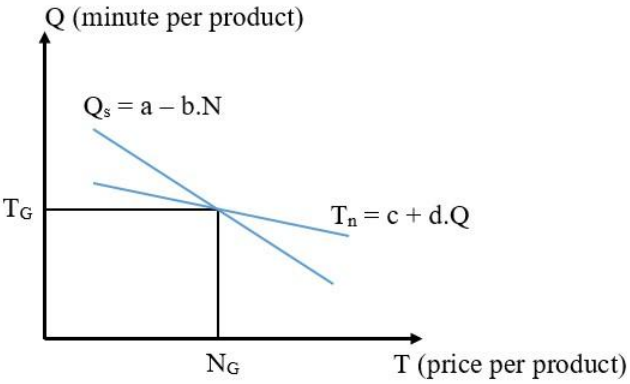

Fig. 8. Graph of the relationship between productivity and product cost.

Solve the system of equations to find the equilibrium point of benefits G(Ts=Tn). Based on product demand, choose the tooling option that is suitable for the specific manufacturing output with: choose a SCT to shorten the production preparation time if the manufacturing output N is smaller than the output at the equilibrium point N_G; choose the manufacturing option of a CCT to increase productivity and reduce product manufacturing costs if the manufacturing output N is larger than the output at the equilibrium point NG. By introducing a CCT, the machining productivity increases of about 131.72% and 257.9% in comparison to the CC in the option 1 and option 2, the cutting time deceases of about 72.06% and 56.85% in comparison to the CC in the option 1 and option 2, and the technology cost decreases of about 42.86% and 63.64% in comparison to the CC in the option 1 and option 2, respectively. The results show that the combination cutting tool is a good solution to improve the machining productivity and cost effectiveness during machining multi-step holes.

4. Conclusions

To reduce manufacturing costs and to increase product competitiveness, there has difference in productivity when machining multi-step holes using CCT and SCT. The study investigates and points out the machining method using CCT has much higher productivity than SCT, due to the reduction of tool change time and travel time of the cutting tool to the machined surfaces. The results are the basis for technologists to refer to in choosing the appropriate cutting tool when machining multi-step holes on metal blanks or in the field of industrial processing. The study also pointed out the issues that it need to be solved when designing and manufacturing CCT. It also opened up further directions such as research on manufacturing field for critical topics such as chip removal and lubrication when machining with CCT, structure and dimensions of each cutting edge in CCT, optimizing cutting modes when machining surfaces with different sizes and technical requirements with CCT, manufacturing and assembly accuracy of CCT, and solving problem of durability of CCT when the cutter sizes at different positions. By introducing a CCT, the machining productivity increases of about 131.72% and 257.9% in comparison to the CC in the option 1 and option 2, the cutting time deceases of about 72.06% and 56.85% in comparison to the CC in the option 1 and option 2, and the technology cost decreases of about 42.86% and 63.64% in comparison to the CC in the option 1 and option 2, respectively.

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