STUDY ON CUTTING CONDITION, PRODUCTIVITY, AND SURFACE ROUGHNESS WHEN TURNING OF HARDENED AISI 1045

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ABSTRACT

Increasing productivity by applying hard and dry machining concepts is the background of this study. The concepts have been well implemented by using CBN and ceramic. However, high cost of CBN and ceramic makes metal cutting industry seeking other possible solutions. The alternative solution offered is carbide due to the development of coating materials and coating deposition technologies. In this research, the use of multilayer CVD-coated carbide (TiN/Al_2O_3/TiCN) when machining hardened steel AISI 1045 (40-45) HRc is studied. The focus of study is on formulating cutting condition and productivity, which represented by metal removal rate (MRR) and volume of material removal (VMR). Turning experiment was carried out by utilizing design of experiment factorial 2^3 with 4 center points. Wear mode including its evolution, machining time and surface roughness (Ra) were recorded. From the results of study, flank wear was observed as the wear mode of multilayer CVD-coated carbide. Cutting condition that could be resulted by the tool was v (250-350) m/min, f (0.14-0.24) mm/rev, a (1.5-2.5) mm with tool life at VB (0.22-0.24) mm was (2.2-19.5) minutes. Under the cutting condition, MRR (53-210) cm3/min and VMR (462-1059) cm^3 were resulted and surface roughness was obtained at medium finish quality or grade N7. Case study was carried out in the related industry and result shows that the productivity of sample product made of hardened steel AISI 1045 was successfully increased about (220-420)%. Those 8 cutting edges of multilayer CVD-coated carbide insert give great contribution to increase productivity.

Keywords: CVD-coated carbide, flank wear, MRR, Ra, VMR.

INTRODUCTION

Surfactant Background of this study is applying hard and dry machining concepts for the purpose of increasing productivity in the metal cutting industry.

Hard machining is applied to machine steel with hardness in the range of (40-60) HRC [1,2]. Although CBN and ceramic tools are widely accepted as the best choices for machining hardened steel but the barricade facing when implementing CBN and ceramic is high cost of cutting tools. Many works have been done to find the alternative solutions and due to the development of carbide grades and its coating materials plus coating deposition technologies; machinists believe that the development of carbides have significant impact to be used for hard machining [3-7].

Coated carbide tools were employed for hard machining of steel with hardness up to 45 HRC [1]. Among many coating materials for carbide, the most frequently used are PVD-applied TiAlN, CVD-applied Al2O3, TiC combined CVD and PVD-applied TiN, TiCN [8-10]. Related to coating deposition method, it was reported that CVD-coated multilayer TiCN/Al_2O_3/TiN carbide insert was observed to be more effective in producing better tool life than the PVD-coated [11].

Among coating materials TiN, TiCN and TiAlN when used for coating carbide tools, the highest wear rate is given by TiAlN due to its high hardness but low toughness film followed by TiN and TiCN when hard turning of AISI 4340 [12]. However, in case of dry turning AISI 4140, TiAlN coated carbide showed a good performance with any cutting speeds less than 260 m/min [13]. In another case, multilayer coated carbide with TiN/TiCN/Al_2O_3/TiN produces higher tool life and lower cutting temperature than TiN/TiCN/Al_2O_3/ZrCN when hard turning of AISI 4340 [7].

There are some characteristics of hard machining, in particular for hard turning [14] that to be considered such as:

a) The rigidity of machine tool because hard turning is a high-speed machining phenomenon with cutting speed normally as high as 250 m/min or even more;

b) Cutting tool with low wearing capabilities is required;

c) Machining without cutting fluid or dry cutting. Under dry cutting, tool tip works at high cutting temperature. The cutting temperature becomes higher and higher when dry cutting is carried out in turning operation due to the accumulation of heat during continuous cutting. High cutting temperature makes annealing process to soften undeformed chip in front of tool cutting edge and thus work material is relatively easier to shear.

The previous researchers have worked upon many facets of hard turning and came up with their own recommendations about the process. In term of cutting condition, the process is essentially a high speed, low feed and low depth of cut.

The cutting speeds, as reported in various works, range from (100-250) m/min or higher, feed from (0.05-

0.2) mm/rev and depth of cut is not more than 2.0 mm [3, 4, 7, 11-14]. Those values depend on some reasons such as material and geometry of cutting tools, value of hardness of work materials, machining operations, quality of surface finish and stability problems. Since there are many kinds of cutting tools and work materials, thus it is necessary to study the suitable cutting condition for certain cutting tool when assigns to hard turning of certain work material under certain machining operation and quality of surface finish.

In this work, an attempt has been made to study the suitable cutting condition for hard and dry turning of AISI 1045 steel using CVD-coated carbide tool. Focus of study is on formulating cutting condition and productivity, which represented by metal removal rate (MRR) and volume of material removal (VMR). Moreover, case study in related industry was made. Sample product made of hardened steel AISI 1045 was machined under cutting condition resulted from this study and productivity was analyzed based on MRR and VMR.

MATERIALS AND METHODS

The cutting tool used in this study was a multilayer CVD-coated carbide tool (from outer to inner: TiN/Al_2O_3/TiCN) SNMG120408 TT8125. It was attached onto tool holder MSDNN 2020K12 to form tool signature of tool cutting edge κ_r 45^0, clearance angle α 6^0, rake angle γ -6^0 and inclination angle λ -6^0.

The AISI 1045 was chosen as work material. The chemical composition and mechanical properties of AISI 1045 are given in Table-1. Prior to testing, the work materials were hardened to gain hardness of (40-45) HRc. All hardened bar specimens (diameter 68 mm, length 360 mm) were then pre-machined in order to remove the surface irregularities and oxidized layer from the outer surface due to hardening processes.

Table-1. Composition and properties of AISI 1045.

Chemical composition (%)			
C	**Si**	**Mn**	**P**
0.430	0.300	0.780	0.035
S	Cr	Mo	Ni
0.035	0.380	0.120	0.060
Mechanical and physical properties			
TS (MPa)	TC (W/mK)	D (kg/m3)	Hardness
650-880	25	7700	185 HRB*
			40-45 HRc^
TS (Tensile Strength), TC (Thermal Conductivity), D (Density) * Equals to 9 HRc, hardness as received / supplied ^ After hardening to meet the requirement of product			

The design of experiment (DoE) factorial 2^3 with 4 center points was used [15]. Based on the results of preliminary testing, it was decided that the ranges of cutting condition were carried out at cutting speed (v) of (250-350) m/min, feed (f) of (0.14-0.24) mm/rev and depth of cut (a) of (1.5-2.5) mm. Those were then arranged into 12 cutting conditions.

The progression of flank wear (VB) was observed using digital camera microscope. This microscope has digital magnification (700-900 x) and the operation is equipped with measurement software. The microscope and a stylus profilometer Surftest SJ210 were used for inspecting machined surface and measuring surface roughness (Ra) resulted by 12 cutting conditions.

RESULTS AND DISCUSSIONS

Tool Wear

The results of the preliminary test for some cutting conditions and the complete of 12 cutting conditions show that flank wear is a dominant wear mode for the multilayer CVD-coated tool used in this study. There were no other wear types observed. The data of cutting time versus evolution of flank wear for all 12 cutting conditions were recorded and the plots are presented in Figure-1 to Figure-3.

As sample of the plot is shown in Figure-4, each plot in Figure-1 to Figure-3 can be divided into 3 phases. Firstly, the evolution of flank wear is initiated by the breakdown wear phase, followed by gradual wear phase and finally sudden wear phase. The evolution of flank wear observed in this study is as widely reported by previous researchers [3-7, 10].

The interesting case on the evolution of flank wear in this study is noted on the slow flank wear progression during gradual wear phase. It means that the width of worn area on flank face is developed steadily and due to this fact, the flank wear has uniform pattern.

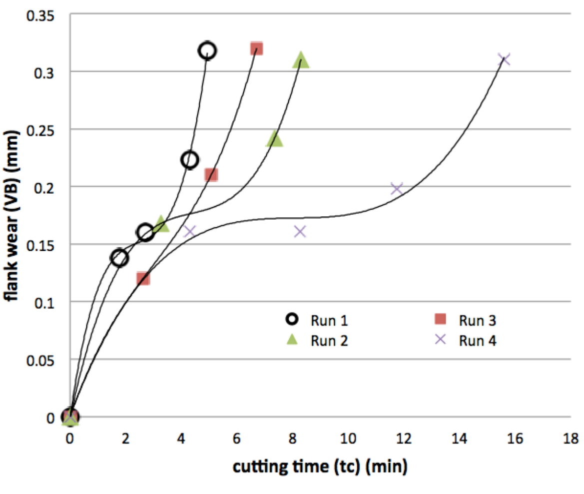


Figure-1. The evolution of flank wear (cutting conditions for Run 1, 2, 3 and 4 refer to Table-2).

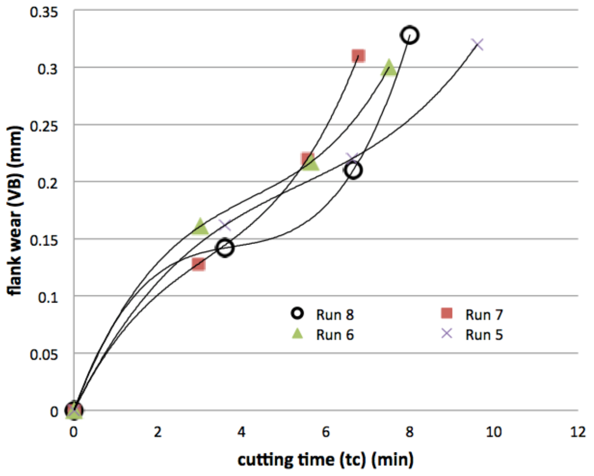


Figure-2. The evolution of flank wear (cutting conditions for Run 5, 6, 7 and 8 refer to Table-2).

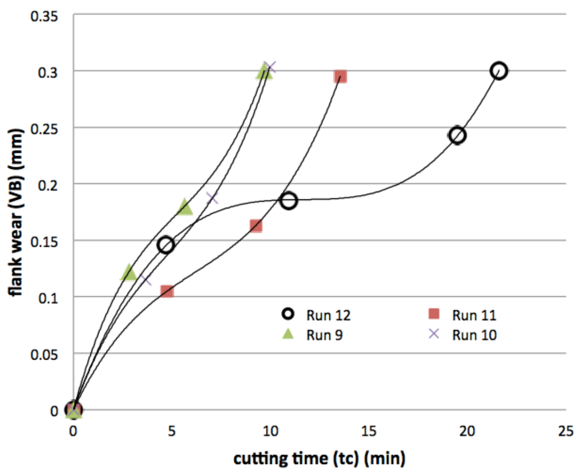


Figure-3. The evolution of flank wear (cutting conditions for Run 9, 10, 11 and 12 refer to Table-2).

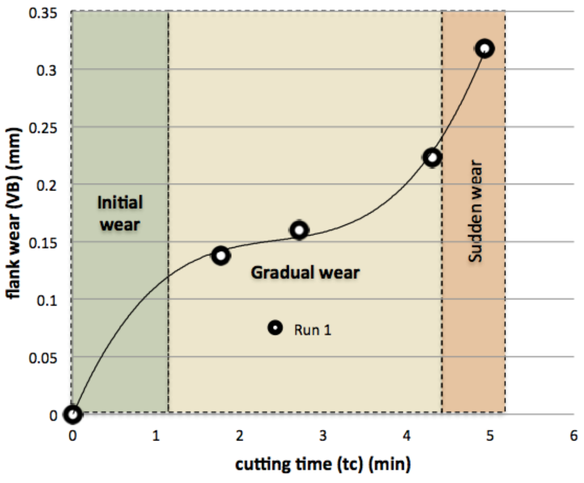


Figure-4. The evolution of flank wear is divided into 3 phases (cutting conditions for Run 1 refer to Table-2).

The continuation of machining to reach VB up to 0.3 mm showed that flank wear was steadily in uniform pattern, but unexpected surface finish was resulted.

The steady evolutions of flank wear in gradual wear phase and the uniform flank wear pattern suffered by multilayer CVD-coated carbide tool in this study are believed due to the effectiveness of coating materials (TiN/Al2O3/TiCN) in combatting the abrasion and adhesion wear mechanisms, which resulting flank wear. The tool producer claims that the low friction coefficient of TiN minimizes friction between undeformed chip (40-45 HRc) and the outer surface of cutting tool during dry turning. The solid lubricant TiN coating acts to lower friction and temperature on flank face and thus, it reduces the action of abrasion and adhesion mechanisms. Based on the data of flank wear progression, the thin outer layer of TiN is predicted working effectively during the evolution of breakdown wear phase.

The steady evolution of flank wear during gradual wear phase depends on performance of the middle layer Al_2O_3 and the inner layer TiCN. Both layers are working side by side in countering adhesion and abrasion. The presence of Al_2O_3 acts as a thermal barrier to prevent adhesion and at the same time, the Al_2O_3 oxide layer formed during continuous cutting protects cutting tool from severe abrasion at elevated temperatures.

After Al_2O_3 is surrendered, the inner layer TiCN is then working to provide an excellent resistance against abrasion. The steady plot of gradual wear phase also indicates that the adhesion strength between TiCN and carbide substrate (WC) is sufficient to overcome concentrated pressure and high cutting force during swarf formation. Unlike the result in [16], it was no coating delamination phenomenon observed in this study. The strong bonding between TiCN and carbide substrate also prevents TiCN layer from coating delamination problem.

When flank wear width greater than VB 0.24 mm and the evolution of flank wear entering the sudden wear phase, molten swarf was observed covering the worn flank face. It is believed that at this stage, TiCN has been completely abraded and thus, the layer is no more serving the cutting tool in combatting adhesion. The absence of TiCN exposes carbide substrate and thus, the steel adhesion occurs and molten swarf covering the tool worn area caused by the remarkable affinity between steel and carbide.

It was witnessed that the color of swarf changed from one testing to the others. The color of swarf indicates the change of cutting temperature from low to high. The swarf color was turned from shiny to brownish and blazing red to bluish. Swarf is more brittle as the increasing of cutting condition. The brittle swarf and some of them are easily to disintegrate when crunched by hand is the evidence of high heat that is being carried out by the swarf from the high temperature zone of swarf formation during hard machining.

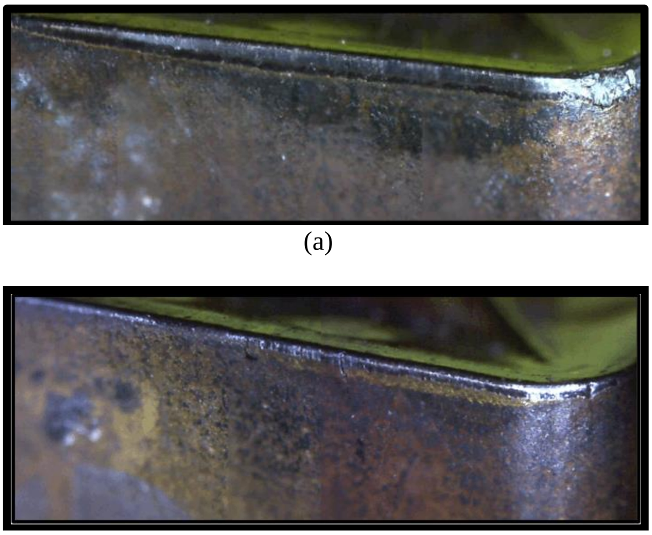
In the case of machined surface, the behavior that interesting to be underlined is the quality of surface finish (medium finish) that was gained by all 12 cutting conditions when flank wear recorded up to VB (0.20-0.24) mm. These VB values were recorded at the end of gradual wear phase of each cutting condition. As discussed before, at this phase all tools tested showed the same pattern of flank wear called uniform flank wear. The typical uniform flank wear pattern experienced by the tool is presented in Figure 5. In this figure, the uniform tool wear pattern is recorded at VB (0.22-0.24) mm when testing at low (v 250 m/min, f 0.14 mm/rev, a 1.5 mm) and high (v 350 m/min, f 0.24 mm/rev, a 2.5 mm) level cutting conditions.

Tool Performance

The performance of multilayer CVD-coated carbide in this study is represented by tool life. The criteria of tool life is derived from tool wear behavior and supported by the quality of surface finish.

Based on the observation and the analysis of tool wear behavior and surface finish, the tool life of CVD-coated carbide used in this study was determined by flank wear with mode of uniform flank wear ranging from (0.20-0.24) mm, while quality of surface finish ranging from smooth turned to medium turned. Data measured from 12 cutting conditions was recorded ranging from (1.90-3.90) micron as shown in Figure-6.

From those 12 cutting conditions, there were recorded that when uniform flank wear was achieved at the end of gradual wear phase VB (0.22-0.24) mm; the shortest and the longest tool life of cutting tool were at 2.2 minutes and 19.5 minutes, respectively.


(a)

(b)

Figure-5. Uniform flank wear at VB (0.22-0.24) mm as the result of testing at: (a) high (Run 1), and (b) low level (Run 12) (refer to Table 2 for cutting condition Run 1 and Run 12)

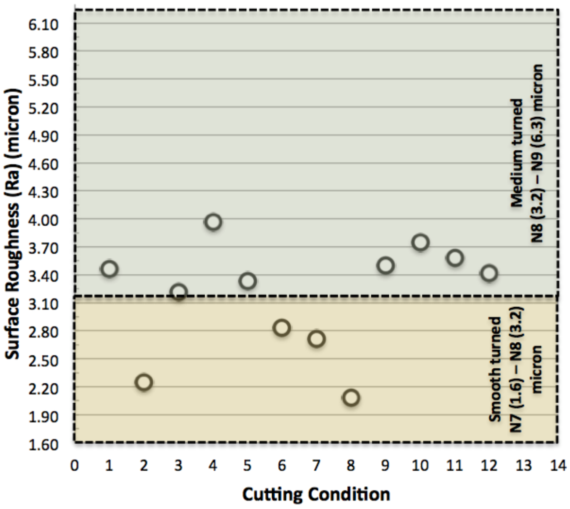


Figure-6. Quality of surface roughness (Ra) resulted by 12 cutting conditions (ranging from smooth to medium turned of grades N7-N9 (1.6 < Ra < 6.3) micron).

The shortest tool life was given by testing number 1 (v 350 m/min, f 0.24 mm/rev, a 2.5 mm), while the longest was given by testing number 12 (v 250 m/min, f 0.14 mm/rev, a 1.5 mm). Tool life for the other cutting conditions, those were recorded in between. All tool life data are presented in histogram and shown in Figure-7. The results of tool life recorded in this study are as expected.

Examination on tool life data and cutting condition show that at low cutting speed (v 250 m/min), the effect of feed is more significant than depth of cut in determining tool life, while at high cutting speed (350 m/min) is in contrary. Moreover, among three variables of cutting condition, cutting speed is prominent to determine tool life. Further information regarding this conclusion refers to Table-2.

Case Study

The complete results of cutting conditions, tool life (TL), material removal rate (MRR) and volume of material removal (VMR) resulted from study are presented in Table-2. Case study to verify data of cutting conditions could be applied in job floor was carried out in this study. Sample product from related industry made of hardened steel AISI 1045 was chosen for case study.

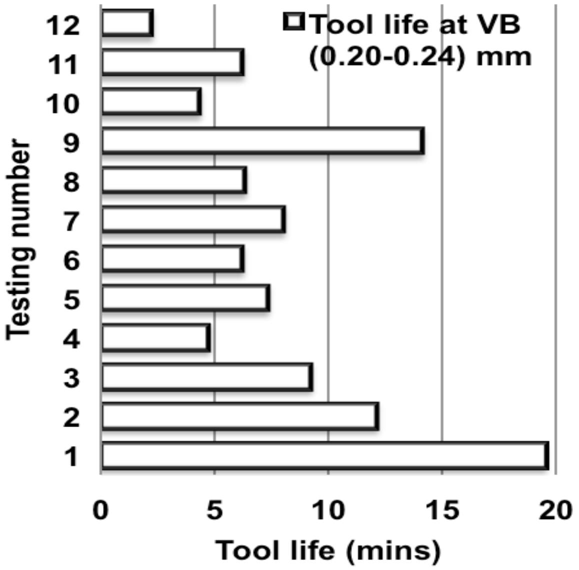


Figure-7. Tool performance (tool life recorded at uniform flank wear VB (0.20-0.24) mm).

The related industry was commonly producing the sample product at cutting condition of v 160 m/min, f 0.1 mm/rev and a 1 mm. The cutting condition was done using brazing carbide under wet cutting condition with quality of medium finish (medium turned). The overview of process planning done by the related industry is shown in Figure-8 [17-19].

After studying the process and listening the expectations of the related industry, the process planning had been modified to fit with hard machining technique. The modified process planning is as follows:

a) Prior to the production process, material AISI 1045 was hardened as the requirement of sample to be produced rather than after Terminal Process (T);

b) Brazing carbide was replaced by multilayer CVD-coated carbide tool (TiN/Al_2O_3/TiCN);

c) Machining process was carried out under dry machining;

d) Product was processed in one cycle from raw material to product (without Terminal Process / T).

In this study, productivity is represented by MRR and VMR. Their values in Table-2 show that implementation of hard machining technique is successful to increase the productivity. Refer to Table-2; those 12 cutting conditions (after) are higher than the value of industrial practiced (before). It can be seen that time to remove raw material to produce sample product or production time to produce sample product is shorter than before. In detailed example, commonly industry spend 21 minutes to remove 336 cm^3 raw material of sample product during production process but now they spend less than 2 minutes by using high level cutting condition (v 350 m/min, f 0.24, a 2.5 mm) or about 6 minutes by using low level cutting condition (v 250 m/min, f 0.14 mm/rev, a 1.5 mm) without sacrificing the quality of surface finish at medium finish (Ra recorded for sample product about 3.0 micron). Also from Table-2, from those 12 cutting conditions, it can be seen that the new cutting condition given by multilayer CVD-coated carbide tool increases VMR up to (138-315)% than before. Note that the value was calculated per cutting edge for multilayer CVD-coated carbide or one re-sharpening cycle for brazing carbide (21 minutes).

In average, related industry uses their brazing carbide for 5 to 6 times of total regrinding and thus, total tool life of brazing carbide will be (105-126) minutes with productivity VMR (1680-2016) cm^3. When those are comparing to multilayer CVD-coated carbide tool that has 8 cutting edges per insert; thus, the total tool life will be (18-156) minutes with productivity VMR (3696-8470) cm3. It is proved that the implementation of hard machining technique under dry cutting using multilayer CVD-coated carbide (TiN / Al_2O_3 / TiCN) is successfully increasing the productivity of related industry in producing sample product for about (220-420)%. Thanks to the performance of multilayer CVD-coated carbide tool (TiN/Al_2O_3/TiCN) with 8 cutting edges, which gives great contribution to productivity.

CONCLUSIONS

Flank wear with uniform pattern is the wear mode of CVD-coated carbide tool (WC-Co/TiN/Al_2O_3/TiCN) when turning of hardened steel AISI 1045 (40-45 HRc) under dry cutting.

Table-2. Cutting condition, TL, MRR and VMR.

No*	v	f	a	MRR	TL	VMR	VMR (%)
0	160	0.1	1.0	16	21	336	100%
1	350	0.24	2.5	210	2.2	462	138%
2	350	0.24	1.5	126	6.2	781	233%
3	350	0.14	2.5	123	4.3	527	157%
4	350	0.14	1.5	74	14.1	1,036	308%
5	325	0.21	2.0	137	6.3	860	256%
6	325	0.17	2.0	111	8.0	884	263%
7	275	0.21	2.0	116	6.2	716	213%
8	275	0.17	2.0	94	7.3	683	203%
9	250	0.24	2.5	150	4.7	705	210%
10	250	0.24	1.5	90	9.2	828	246%
11	250	0.14	2.5	88	12.1	1,059	315%
12	250	0.14	1.5	53	19.5	1,024	305%

* 0 (industrial practiced); (1-12) testing number in this study

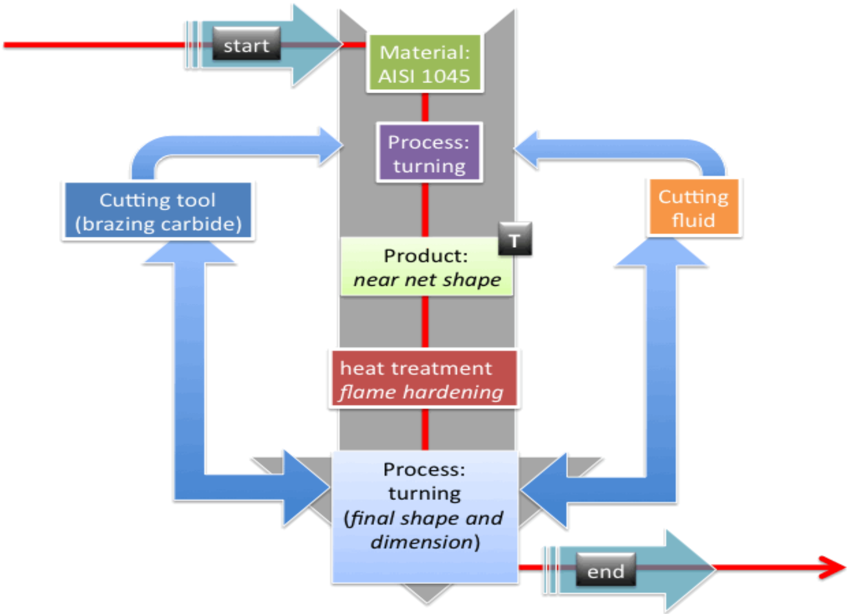


Figure-8. The overview of process planning in related industry when producing sample product (T = Terminal Process).

Coating materials (TiN/Al_2O_3/TiCN) deposited onto carbide are observed effective in combatting the abrasion and adhesion wear mechanisms. Solid lubricant TiN coating acts to lower friction and temperature while the presence of Al_2O_3 acts as a thermal barrier to prevent adhesion and at the same time, the Al_2O_3 oxide layer formed during continuous cutting protects cutting tool from severe abrasion at elevated temperatures.

Adhesion strength between TiCN and carbide substrate (WC) is sufficient to overcome concentrated pressure and high cutting force during swarf formation because no coating delamination phenomenon is witnessed.

Multilayer CVD-coated carbide tool can be operated for hard turning AISI 1045 with hardness of (40-45) HRc under dry cutting in the range of cutting condition: v (250-350) m/min, f (0.14-0.24) mm/rev, a (1.5-2.5) mm. As the quality of surface finish is concerned, quality of surface finish resulted by the tool ranging from smooth turned to medium turned or ranging from grades N7 to N9. Data measured from 12 cutting conditions was ranging from (1.90-3.90) micron at the width of flank wear at VB (0.22-0.24) mm. The values of surface finish and flank wear are determined as tool life criteria.

Related to cutting conditions and tool criteria, the shortest tool life is 2.2 minutes resulted by v 350 m/min, f 0.24 mm/rev, a 2.5 mm and the longest tool life is 19.5 minutes resulted by v 250 m/min, f 0.14 mm/rev, a 1.5 mm.

As MRR and VMR are represented productivity and taking the sample product with process planning of related industry as the basis of comparison in case study; it is proved that the implementation of hard machining technique is successfully increasing the productivity of sample product about (220-420)%. The performance of multilayer CVD-coated carbide tool (TiN/Al_2O_3/TiCN) with 8 cutting edges gave great contribution to productivity.

NOMENCLATURE

v	cutting speed	m min^{-1}
f	feed	mm rev^{-1}
a	depth of cut	mm
MRR	material removal rate	cm^3 min^{-1}
VMR	volume of material removal	cm^3
TL	tool life	min
VB	flank wear width	mm
Ra	surface roughness	micron

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