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Machining and Machinability of Tool Steels: Effects of Lubrication and Machining Conditions on Tool Wear and Tool Life Data

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Abstract

The machinability of materials depends on various factors including the workpiece materials and condition, the cutting tool data and the machining conditions (wet or dry). Most tool life data found in literature are established using dry machining conditions. This makes it difficult to make suitable comparison with wet machining conditions, to compute cost effective machining conditions or to simulate the machining processes, especially for newly developed alloys. In the present paper, the machinability of tool steels is investigated using dry and wet milling process. Tools steels with different compositions and hardness were milled using carbide inserts and the tool wear/tool life performance studied. The coefficients of the Taylor model of tool life were established for each steel and then used to compute the economically speeds and the maximum productivity speeds. It was found that the dry milling is more advantageous for the tested steels, especially for roughing operations, but the tool life data in dry machining conditions was very sensitive to materials compositions and hardness compared to wet machining conditions.

Keywords: Tool steels; Milling; Tool wear/Tool Life; Taylor Data; Costs

1. Introduction

Several factors affect the machinability of materials; They include the cutting data and conditions (cutting speed, feed, depth of cut, operation and lubrication), the tool data (material and coating, geometry), and the material (composition, hardness and machining conditions [1, 2]. An easy to machine material will have a direct effect on machining costs, cycle time and productivity and thus on the industry competiveness [2, 3]. Dry machining, for example, was found to be appropriate for cost reduction and for protecting the environment and the worker's health [2]. The cost of using cutting fluids, about 17% of the part manufacturing costs [4], can easily exceed that of the cutting tools, [5]. The machining performance (tool wear/tool life, surface finish and residual stresses) of mould steels was found to be influenced by the cutting mode and the material's melting processes [6]. Under appropriate machining conditions, comparable tool life could be obtained in dry and in wet machining of steels [7]. It is therefore understandable that efforts be put on developing materials with better machinability and in searching for cost-effective machining conditions and data.

In the current research work, the tool wear and tool life when milling four mould steels (listed in Table 1, chosen by the industrial partner of the project) is studied during under dry and wet machining conditions. The alloys tested were comparable two by two in terms of hardness but had slightly different chemical compositions, Table 1.

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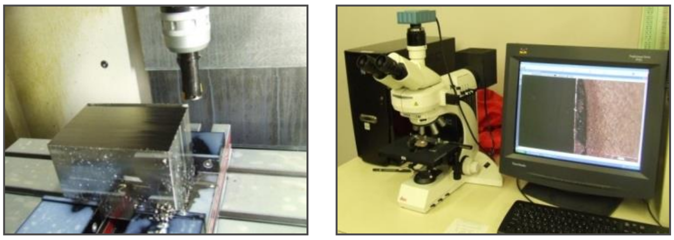
2. Experimental procedure

The tool wear/tool life testing was conducted using industrial scale equipment and stable conditions. The material blocks received from a forging company were first machined roughly using a 4-inch (101.6 mm) face mill. The machining operations were carried on a 3-axis CNC vertical milling machine (MAZAK NEXUS 410A, Maximum rpm: 12000 rev/min; Power: 25 HP). The cutting tool consisted of a 38.1 mm diameter milling tool with two multilayer coated (TiN/TiCN/TiN) carbide inserts (ISO code XPMT150412L KC725M) : 11º clearance angle; 1.2 mm nose radius. The operations were carried out dry or wet (using a cutting fluid supplied flood). The fluid was a mix of mineral oil (55%), water (4%) and Chlorinated paraffin additives. The milling parameters were the following:

Cutting speed: 75-300 m/min; Feed rate: 0.1016 mm/tooth
Axial depth of cut: 2.54 mm; Radial depth of cut: 12.7 mm



a) b)

Fig. 1: Experimental setup and measurement system for tool wear testing and measurement

Fig. 1 presents the experimental set up and the tool-wear measurement system. The workpiece material block was machined for a given period of time (2 to 5 minutes depending on the used cutting speed), after which the machining operation was stopped and the inserts observed under an optical microscope equipped with a digital camera (Fig 1b). The flank face of the insert was photographed and the pictures stored for further measurements. The two inserts were once again remounted on the tool holder and used to continue the cutting process. These steps were repeated until the average width of flank wear, VB, exceeded 0.3 mm and the tool life was estimated. The measurements were realised following the ISO 8688-2 [8]. The cutting forces and the surface finish were also recorded and analyzed but are the object of the current presentation.

Table 1. Tested materials' composition & hardness.

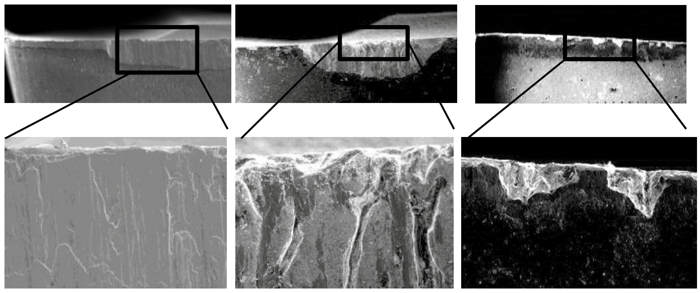
Materials ID	SF-5	SF-2312	SF-2000	SP-300
Hardness (HB)	300	300	341	341
Chemical composition (weight %)				
Carbon (C)	0.34	0.38	0.34	0.25
Manganese (Mn)	0.60	1.50	0.80	1.30
Sulphur (S)	0.006	0.07	0.006	0.02
Silicon (Si)	0.40	0.30	0.40	0.15
Chrome (Cr)	1.25	2.00	1.75	1.30
Molybdenum (Mo)	0.30	0.20	0.45	0.40
Copper (Cu)	-	-	-	0.08

3. Results and discussions

3.1. Tool wear mechanisms and patterns

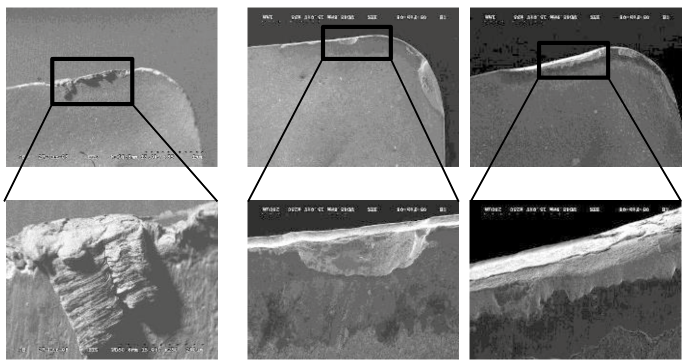
The tool wear patterns observed on cutting inserts were both flank and edge wears and the wear mechanisms include the regular abrasive wear, micro chipping, thermal fatigue and Notch wear. The flank wear occurred during dry milling was a progressive process (Fig. 2a) while during wet milling, flank wear occurs mainly as a result of thermal cracks (Fig. 2b) or chipping (Fig 2c), depending on the material machined and the cutting speed used, with the number of cracks observed increasing with the cutting speed. In fact, during milling, each insert undergoes an intermittent cutting; the insert heats up during cutting, and cools down when it is taken out of the material, this leads to thermal cracks for the lubricated modes.

The observation of the rake face of the cutting inserts revealed different wear mechanisms and patterns depending on the cutting conditions used and the materials cut. The wear mechanisms observed when machining dry were: i) adhesive wear (Fig. 3a) occurring when the speed used was high and the temperature on the cutting edge high accordingly; ii) edge progressive wear and cracks (Fig. 3b); iii) erosive and progressive wear following the coating pilling or destruction as a result of heat and abrasive action of the chips (Fig. 3c)



a- Dry milling : progressive wear | b-Wet Milling : Thermal cracks | c) Wet milling: Edge chipping

Fig. 2: Tool wear patterns on the flank face for dry and wet milling (Cutting velocity of 125 m/min, after 18 minutes)



a) Build-up-edge | b) edge wear and cracks | c) Coating pilling & erosive wear

Fig. 3: Some tool wear patterns observed on rake face during dry milling

3.2. Tool wear progression and tool life

The average flank wear, VB, was measured on each of the two inserts used and the average value was recorded and plotted versus the cutting time for the four materials in dry and wet conditions, respectively. Fig. 4 and 5 summarize the tool wear progression for the SF2000 steel in wet and dry machining conditions. As expected, the increase in cutting speeds led to the increase of tool wear rates for the two lubrication modes.

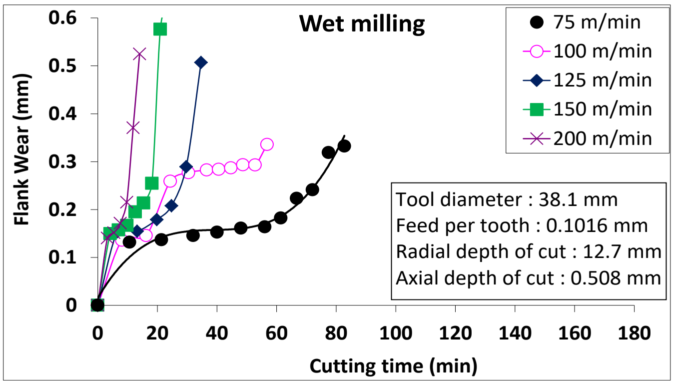


Fig. 4: Wear curves of SF-2000 material (341 HB) milled with coolant at different cutting velocities

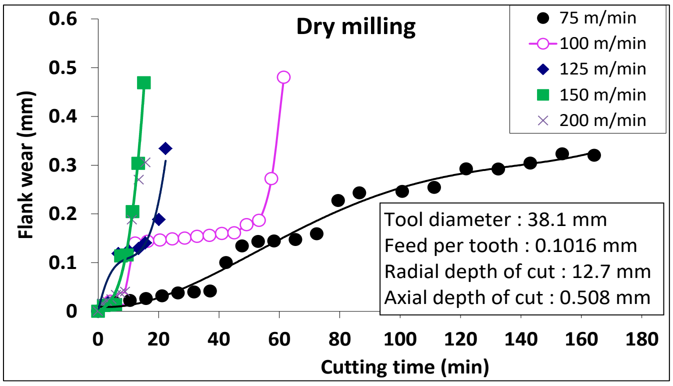


Fig. 5: Wear curves of SF-2000 material (341 HB) for dry milling at different cutting velocities

Figs 6 and 7 present the tool life and cutting speed relationships when milling the tested mould steels. The tool life was extracted from the tool wear curves using a tool life criteria of VB = 0.3 mm. No significant difference was found when milling the tested steels under dry conditions, especially when milling at high cutting speeds (Fig. 7). In fact at these speeds, the cutting fluid does not remain in the cutting zones due to centrifugal forces, therefore the tool life is relatively short for all the steels tested, independently of their hardness. At cutting speeds below 100 m/min, the SP300 steel behaved better than the others: better tool lives were obtained, Fig. 7.

Under dry milling conditions, there was a remarkable difference between the behaviour of the tested steels (Fig. 6). Machining steels with low hardness resulted in better tool life as compared to steels with high values of hardness. In general, the tool life obtained at dry conditions was higher than the on obtained during wet milling conditions. For example, while under wet milling, the tool life obtained for a cutting speed of 200 m/min was only 10 minutes for the four tested steels (Fig. 7), under dry conditions, the tool life for the same speed varied from 12 to 33 minutes. This result is consistent with findings of Vieira, et al [9], can be explained also by the thermal fatigue already discussed.

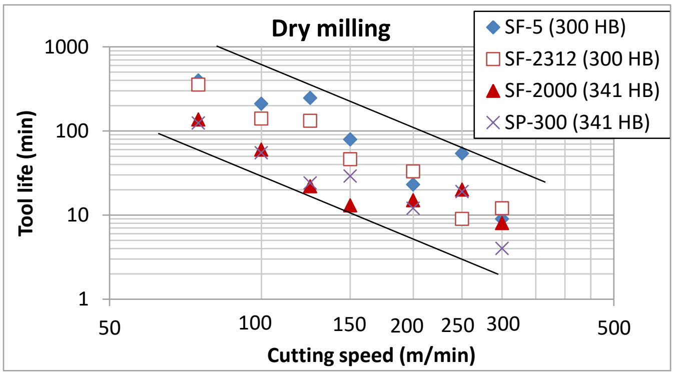


Fig. 6: Tool life vs cutting speed in dry milling

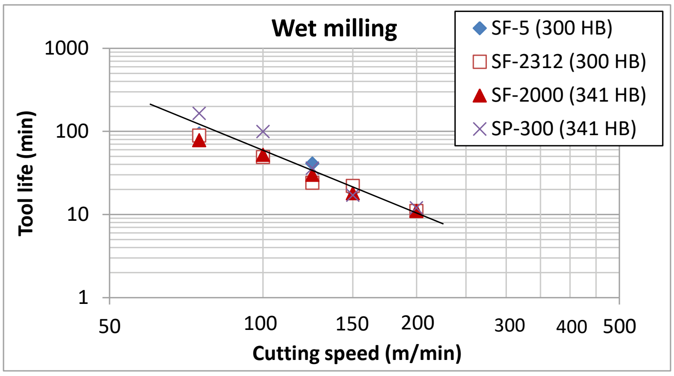


Fig. 7: Tool life vs cutting speed in wet milling

The Tool life is related to the cutting speed used by the Taylor relationship (Eq. 1).

$$V_c \cdot T^n = C \qquad (1)$$

Where Vc is the cutting speed, (m/min)
T is the tool life (min)
n and C are constants to be determined.

Eq. 1 can help establishing optimal cutting data for machining. The change on these coefficients when the lubrication modes were changed can be attributed to the difference on tool wear mechanisms. It appears that the n exponent varies with the cut materials, especially when machining wet. This difference should be taken into account when searching for critical cutting speeds or when optimizing the machining conditions.

Table 2 summarizes the coefficient of Taylor relation for the materials and conditions tested. The Taylor exponent varied less under dry machining and remains about 0.3-0.4. It might be difficult to notice the differences between the tool performance or the machining economics when looking at the Taylor coefficient and exponents (Eq. 2-8). To further illustrate it, the cutting speeds for 60 minutes tool life were extracted and use to build the graph presented in Fig. 8. The better cutting speeds obtained were about 150 m/min for the SF5 and the SF 2312 steels under dry conditions while for others, the cutting speed rarely exceeded 100 m/min. The use of higher speeds will lead to better productivity and therefore low cycle times and reduced machining costs.

Table 2: Taylor model for the wet milling processes

Materials	Hardness (HB)	Taylor' Model Equations for **wet milling**	
SF-5	300	$V_c \cdot T^{0.435} = 568$	(2)
SF-2312	300	$V_c \cdot T^{0.54} = 748$	(3)
SF-2000	341	$V_c \cdot T^{0.47} = 615$	(4)
SP-300	341	$V_c \cdot T^{0.32} = 417$	(5)

Table 3: Taylor model for the dry milling process

Material	Hardness (HB)	Taylor' Model for **dry milling**	
SF-5	300	$V_c \cdot T^{0.30} = 508$	(6)
SF-2312	300	$V_c \cdot T^{0.38} = 712$	(7)
SF-2000	341	$V_c \cdot T^{0.35} = 413$	(7)
SP-300	341	$V_c \cdot T^{0.41} = 533$	(8)

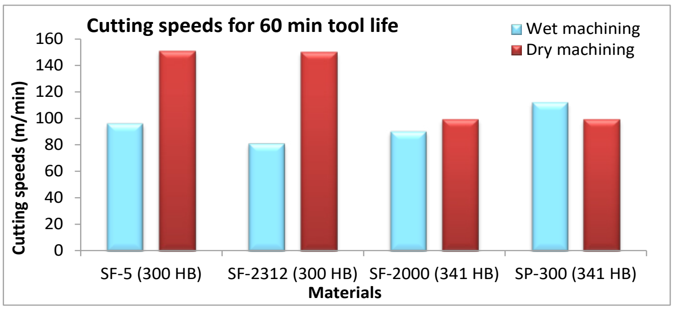


Fig. 8: Comparison of cutting speeds for 60 minutes tool life for each tested steel in wet and dry conditions

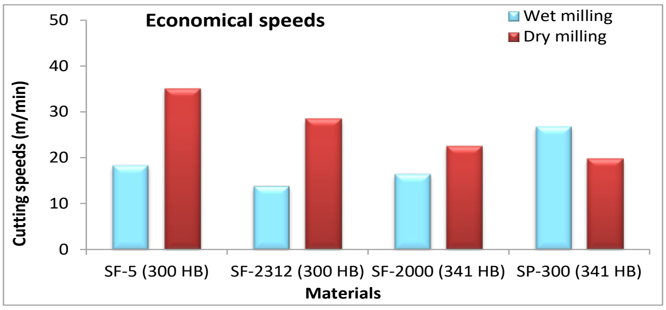


Fig. 9: Economical cutting speeds for each tested steel in wet and dry conditions

Figs 9 and 10 compare the effects of lubrication and workpiece materials on economical speed (Fig. 9) and on maximum productivity speed (Fig 10). In general the use of lubrication led to lower economical speeds and to low maximum productivity speeds. Materials with similar hardness had comparable performance. These speeds were computed using the Taylor data (Tables 2 and 3), equations available in Machining Data Handbook, and the following constants:

Labour rate ($/min)	1.5	Feed per tooth (mm)	0.10
Tool indexing time (min)	0.13	Number of teeth	2
Tool holder cost ($)	100	Insert cost ($/insert)	5
Tool diameter (mm)	38.1		

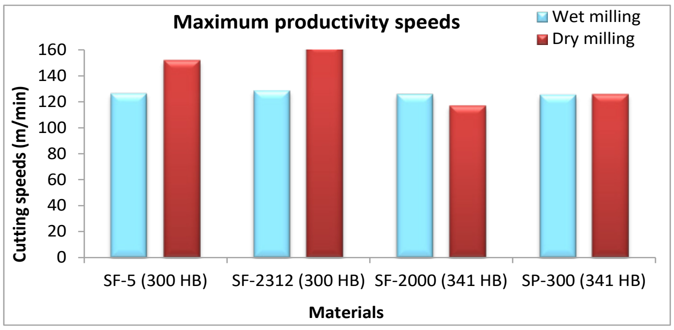


Fig. 10: Maximum productivity speeds for each tested steel in wet and dry conditions

Conclusion

The use of lubricant during the milling of the tested tool steels affected the tool wear mechanisms, the tool life, the Taylor's model data, the economical speed and the maximum productivity speed. Therefore it is expected the machining costs and the cycle times will be affected accordingly.

The dry milling outperformed the wet milling operations, especially at low and moderate cutting speeds, partially because of the change in wear mechanisms (thermal fatigue when using lubricant). In general, for all tested wet machining conditions, there was no difference between the tested workpiece materials. This is a consequence of the type of tool wear observed. During dry milling, materials with low hardness led to better tool life than harder materials.

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