INVESTIGATION OF THE RELATIONSHIP BETWEEN CUTTING FORCE AND CUTTING TOOL WEAR WITH TECHNOLOGICAL PARAMETERS WHEN TURNING HARDENING WITHOUT COOLING SKD11 STEEL

KHẢO SÁT MỐI QUAN HỆ GIỮA LỰC CẮT VÀ ĐỘ MÒN DỤNG CỤ CẮT VỚI CÁC THÔNG SỐ CÔNG NGHỆ KHI TIỆN CỨNG KHÔNG LÀM MÁT THÉP SKD11

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Abstract - This paper presents the survey results of the relationship between the value of cutting force and the tool flank wear with the cutting parameters in dry turning SKD11 steel with a hardness above 54HRC. With the aim of surveying the change in cutting force and flank wear, each experiment was carried out with several successive cuts until the cutting tool was destroyed. At the end of each cut, the values of cutting force and tool wear are measured and recorded. The experimental results obtained from the force sensor are handled with care. The graphs show the relationship between cutting force and tool wear over time and over the established machining length. The results of independent evaluation of the influence of cutting parameters can be used as a basis for establishing experimental models to evaluate the simultaneous influence of technological parameter pairs on cutting force and tool wear.

Key words - Hard turning; cutting force; tool wear; cutting parameters; high-speed turning

Tóm tắt - Bài báo này trình bày kết quả khảo sát mối quan hệ giữa giá trị lực cắt và độ mòn mặt sau của dao tiện với các thông số công nghệ khi gia công vật liệu thép SKD11 với độ cứng đạt trên 54HRC. Với mục tiêu khảo sát sự thay đổi lực cắt và độ mòn mặt sau dụng cụ cắt, mỗi thí nghiệm được tiến hành với nhiều lượt cắt liên tục cho đến khi dụng cụ cắt bị phá hủy. Khi mỗi lượt cắt kết thúc, lực cắt và độ mòn dụng cụ được đo lường và ghi nhận lại. Các kết quả thực nghiệm thu từ cảm biến lực được xử lý cẩn thận. Các biểu đồ hiển thị mối quan hệ giữa lực cắt và độ mòn dụng cụ cắt theo thời gian và theo chiều dài gia công được thiết lập. Kết quả đánh giá độc lập ảnh hưởng của các thông số cắt có thể được sử dụng làm nền tảng để thiết lập các mô hình thí nghiệm đánh giá ảnh hưởng đồng thời của các cặp thông số công nghệ tới lực cắt và độ mòn dụng cụ.

Từ khóa - Tiện cứng; lực cắt; độ mòn dụng cụ; thông số cắt; gia công cao tốc

1. Introduction

In the machining process, many physical phenomena occur that affect the quality and productivity such as vibration, friction, cutting force and tool wear [1, 2]. These factors all greatly affect product quality such as machining errors, mechanical properties and their ability to work. The causes for these phenomena to occur all stem from the selection and change of machining factors such as cutting parameters (cutting speed, depth of cut, tool feed speed), material of workpiece and tool, and the rigidity of the technology system.

The mechanism that forms the surface of the product and controls the machining process change is the cutting force (CF). It clearly reflects normal or abnormal machining conditions such as tool wear (TW), tool breakage, cutting heat and vibration. It is necessary to analyze the relationship between CF and cutting parameters (CP), tool wear, and vibration. The CF changes continuously throughout the machining process. These values are measured and analyzed in [3] during high-speed milling of aluminum alloys. The CF value is determined in the stable region and averaged. A mathematical model is built in [4] to predict the CF when microdrill cutting. This factor prediction model was also developed in [5] in surface milling based on FEM and NURBS. The stochastic model of the CF is built and analyzed in [6] with the turning process through orthogonal CF measurements. The important results of this study show that the variance of the CF measurement signal is in the range of 4% - 9% of the mean value. The value of the marginal CF was investigated in [7] when milling the inclined plane with a cutter for hard alloy 55NiCrMoV6. The technique of signal processing to measure CF is described in detail in [8] when using a tunneling machine. The CF measurement and force spectrum analysis are described in [9] with milling through a PVDF thin film sensor.

Wear and failure of cutting tools are serious problems in cutting in general and high-speed machining of high hardness materials in particular. It not only increases the cost of production but also reduces the quality of the product. Tool wear interrupts machining and substantially increases machining preparation time. TW accounts for about 20% of total machine downtime, leading to dramatic increases in production costs [10]. Besides, tool wear, tool breakage can lead to consequences, such as unsatisfactory workpieces, or worse, can lead to machine failure. Therefore, to improve product quality, manufacturers need to monitor the state of the tool during actual machining to analyze the life of the tool, and decide when the cutting tool needs to be changed. Furthermore, this monitoring ensures timely tool change is carried out before the tool becomes inoperable, in order to eliminate the risk of damage to the part, as well as to the machine [11]. Tool wear is a complex problem [12] and it depends on many factors in the machining process such as the characteristics of the cutting tool (cutting tool geometry, cutting tool material, heat resistance and wear resistance), cutting parameters (depth of cut, cutting speed and feed rate, coolant), workpiece (material ingredients, material mechanical properties), physical phenomena during machining (friction, cutting force, vibration, cutting temperature) [13-15]. The cutting speed factor in the study [13] is of major interest when evaluating its influence on TW, surface quality and CF with different materials. The influence of technology regime when machining TiMMCs alloys on wear value and tool life is clarified in [15]. Among the above wear types, the flank wear (VB) is the most important because when machining the back surface is always in contact with the machined surface. According to ISO 3685:1993 and ISO 8688-2:1989, tool life is usually estimated by the wear value VB. The wear characteristics of the tool are mostly expressed as a graph of wear value against cutting length or machining time [16]. Accordingly, VB directly affects the dimensional accuracy and surface quality of the work piece. On the other hand, VB is also easy to determine because optical measuring instruments can be used to check [17]. The evaluation of the influence of cutting parameters on CF, vibration, TW in general and the relationship between these factors should be considered in detail. They can completely be used to forecast and monitor the machining process, making a significant contribution to reducing costs and improving machining productivity. The establishment of the relationship between CF and factors related to product quality has been described in [18]. The relationship between the value of the VB area and the components of the CF is detailed in [19]. Multivariate regression techniques and artificial intelligence networks are used in [20] to build the VB-CF relationship when machining composites. For milling, this relationship is considered in [21]. The force measurement signals and TW values are used to build the wear classification and monitoring system. The characteristics of TW and CF are analyzed in [22] when turning AISI 4340 steel. Accordingly, the internal relationship between TW factors and CF is also considered. The instantaneous CF components are calculated based on the change of the cutting area or cutting parameters. The problem of wear related to significant variations in forces and vibration signals is detailed in [23].

In recent decades, hard turning technology has been studied to replace grinding technologies in finishing hardening steel products [14, 24, 25]. During hard turning, thanks to the single-blade tool it is possible to precisely adjust the cutting angle and thus easily machine complex surfaces of the product. Compared with grinding, hard turning has many outstanding advantages in economic and ecological aspects [26]. The most significant advantage of hard turning is that it is possible to use one tool and still machine many different shaped parts by varying the toolpath. Meanwhile, if you want to sharpen other detailed shapes, you must fix the stone or change another stone. In particular, hard turning cn process complex profiles that are difficult to achieve with grinding. Moreover, hard turning can also perform dry machining [27, 28] without the use of cold fluids, so it does not affect the environment and workers' health [29]. However, hard turning also requires a technological system with high rigidity and high accuracy [30].

This paper presents preliminary research results on the relationship between CF and TW of cutting tools when turning hard and dry SKD11 steel after heat treatment with hardness reaching 55(±1)HRC. Based on a series of tests performed with different cutting parameters, the CF and TW are measured continuously over time and cutting length. The research results give some basic statements about the above relationship and can be used as a basis for building an experimental model to study in detail the influence of cutting parameters on the value of the CF and TW. Moreover, this relationship can be considered to study and build a monitoring and warning system for tool wear during machining.

2. Materials and methods

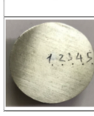
2.1. Setup experimental system

The whole experiment was carried out on a HASS-ST10 lathe. Select SKD11 steel billet that has been heat treated to reach hardness 54÷56HRC, billet length is 300mm, billet diameter is 30mm (Figure 1). One test piece is cut from each workpiece corresponding to each experiment to perform turning with 5 different diameter values. Hardness is measured at the five diameter locations, respectively (Figure 1b). Hardness measurement results at different workpiece diameter values give approximately the same results. This shows that the hardness in the outer and inner layers is not different. The chemical composition of the embryos is described in Table 1.

Table 1. *Chemical composition SKD11 steel*

Ingredients	%
C	1.45-1.65
Si	≤ 0.4
Mn	≤ 0.35
Cr	11.0-12.5
Ni	11.0-12.5
Mo	0.4-0.6
Va	0.15-0.3

(a) Workpieces

Workpiece	Position										Result	Goal (HRC)
	1		2		3		4		5			
	D(mm)	HRC	D(mm)	HRC	D(mm)	HRC	D(mm)	HRC	D(mm)	HRC		
	2.6	55.5	8.2	55.5	15.2	55.5	22.6	55.5	29.6	54	Done	54÷56

(b) Hardness measurement results in different positions

Figure 1. *Workpiece SKD11*

For cutting tools, choose the CBN insert piece with symbol TNP-VNGA168408G2 (MB8025) of MITSUBISHI with specifications including IC=9.525mm (Insert IC Size); LE=16.606mm (Insert Cutting Edge Length); S=4.76mm (Insert Thickness); RE=0.8mm (Corner Radius); D1=3.81mm (Insert Hole Size). The

9257BA-Kistler 3-component dynamometer is used to record the variation value of the CF in the three directions x, y, z respectively Fx, Fy, Fz. The instrument is supplied with the control box 5233A1, A/D converter, NI USB-6009 receiver (DAQ) and DASYLab 10.0 software. The tool wear value was determined after each machining interval with the help of an electron microscope UM012C. The experimental system is depicted in Figure 2.

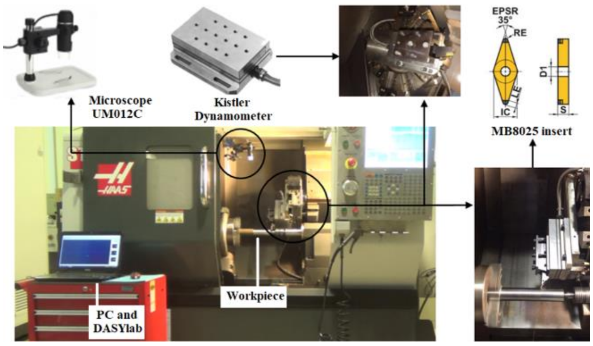


Figure 2. *Machining and measuring systems*

Based on 03 main bases to select cutting parameters for experiments. First, based on the manual of cutting parameters from the cutting tool supplier. Second, from reference to previously published works with related experiments. Third, from the preliminary experiments that were performed initially on the type of material used in this study. The technical parameters are described in Table 2. In which, V_c (mm/min) is cutting speed, s (mm/rev) is feedrate and a_p (mm) is depth of cut.

Table 2. *Cutting parameters*

Parameters	Level 1	Level 2	Level 3
V_c (mm/min)	80	125	170
s (mm/rev)	0.07	0.11	0.15
a_p(mm)	0.1	0.175	0.25

Perform continuous layer-by-layer finishing machining. For each cut, the tool runs correspond to the actual cutting distance L_c (mm). After each cutting length L_c, the cutting tool moves to the electron microscope position, the maximum height VB_{max} is measured on the computer with the help of MicroCapture software on the background of digital images taken and record once. The test is stopped when the tool wear height reaches $VB_{max} \geq 0.6$(mm). At that time, the new turning tool insert will be replaced. Each experiment used one insert piece. It should be noted that, the actual cutting length L_c is not the travel of the tool along the length of the workpiece (also known as the programmed toolpath), but L_c is the distance that the tool is in continuous contact with the workpiece when it is rotating with spindle speed n (rev/min) and the tool moves with feedrate s (mm/rev). This actual cutting length value accurately represents the length that the cutting tool works on the workpiece during machining and is the basis for assessing tool wear. In turning machining, after the tool has completed one toolpath (the end of the programmed length L (mm), the workpiece diameter changes. To ensure that the cutting speed remains constant during each cutting stroke while the workpiece diameter changes, the spindle speed (n) must change accordingly. Specifically, the spindle speed is determined according to the change in the workpiece diameter (D) as follows

$$n = \frac{1000V_c}{\pi D} \quad (1)$$

In which, V_c has a constant value.

Consider the feedrate to be s (mm/rev). This shows the long distance that the cutting tool reciprocates after each revolution of the workpiece. So, if the programmed length (cutting toolpath length) is L (mm), the workpiece needs to be rotated L/s revolution. On the other hand, for each revolution of the workpiece, the cutting tool is in constant contact with the workpiece exactly equal to the circumference of πD (mm). Therefore, for L/s revolution of the workpiece corresponding to the programmed length L (mm), the actual cutting length L_c (mm) is determined:

$$L_c = \frac{L}{s}\pi D \quad (2)$$

In which, the actual cutting length L_c and the feed rate s (mm/rev) are given and remain constant after each cutting stroke. This is the basis for programming the machining for the above experiments.

2.2. Measurement data processing

The measuring signal is the components of the shear force including F_x (axial force), F_y (radial force), F_z (tangent force). The total force F_{total} is determined as follows:

$$F_{Total} = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (3)$$

The components of the cutting force when turning and the location of the tool wear value are depicted as shown in Figure 3a and Figure 3b. It should be noted that the rotary direction of the spindle in Figure 3a is clockwise.

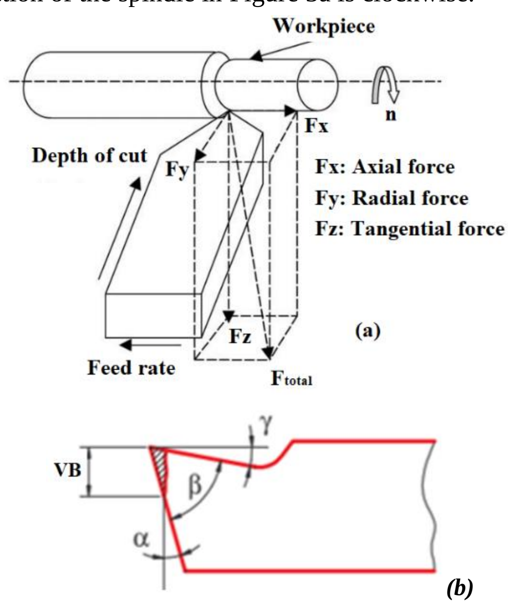


Figure 3. *Cutting force components and tool wear measurement position*

Figure 4 shows the interface when measuring and displaying the cutting force components. The CF value is presented in the form of a histogram.

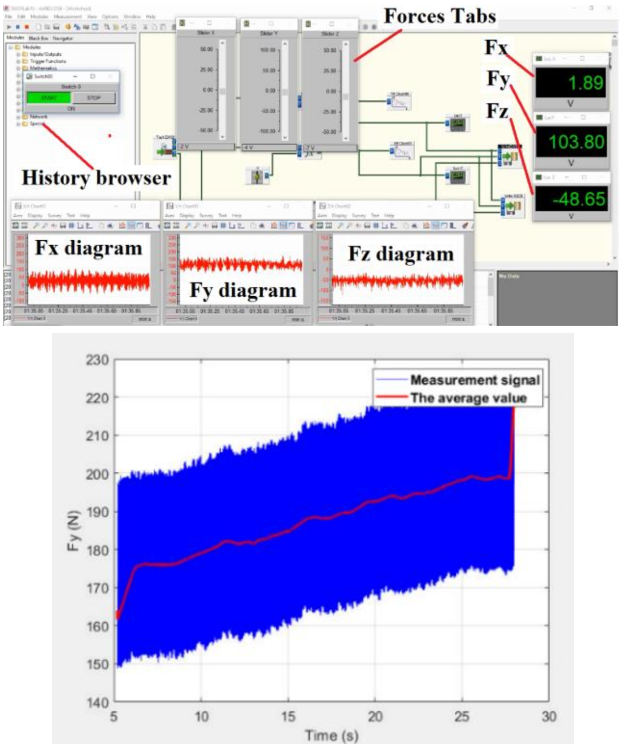


Figure 4. *Measurement interface and signal processing results*

2.3. Experimental results and discussion

The results after data processing and measurement are shown in Table 3. Specific values of CF are shown in the link to the following document: experimental results.

Accordingly, Table 3 clearly describes the state of the cutting tool after the total number of cuts and the total machining time to the broken state. For example, experiment 1 (Ex 1) showed that the cutting tool was destroyed after 18 cuts (each with a real cutting length of 100 m) for a total machining time of 663(s). Similarly, experiment 2 (Ex 2) describes a cutting tool that has made 25 cuts with a total machining time of 1017(s) without failure. Whether the tool is brocken or not brocken depends heavily on the cutting parameters and physical phenomena in the machining process. They are analyzed in more detail below.

Table 3. *L_c value and turning time*

TN	ap (mm)	Vc (m/min)	S (mm/rev)	Lc (m)	Number of cuts	Total time (s)	Cutting tool status
1	0.1	170	0.07	100	18	663	Broken
2	0.1	125	0.11	100	25	1017	Unbroken
3	0.1	170	0.11	100	24	643	Broken
4	0.175	80	0.07	100	24	1813	Broken
5	0.175	80	0.11	100	20	1038	Broken
6	0.175	125	0.11	100	24	915	Broken
7	0.25	80	0.07	100	25	2111	Broken
8	0.25	125	0.07	100	26	557	Broken
9	0.25	170	0.07	100	16	607	Broken
10	0.25	125	0.11	100	24	814	Unbroken

Table 4 presents the results of measuring tool wear values for each cut in 10 experiments (Ex). Accordingly, experiment 2 (Ex 2) and experiment 7 (Ex 7) showed that the cutting tool achieved 25 cuts. Experiment 8 (Ex 8) achieved the maximum number of cuts of 26 cuts.

Table 4. *Tool wear value (mm)*

No.	Ex1	Ex 2	Ex 3	Ex 4	Ex 5
1	0.1530	0.1240	0.116	0.1070	0.070
2	0.1550	0.1250	0.125	0.1100	0.101
3	0.1610	0.1280	0.185	0.1150	0.171
4	0.1650	0.1310	0.193	0.1170	0.182
5	0.1660	0.1400	0.231	0.1180	0.186
6	0.1670	0.1440	0.232	0.1190	0.192
7	0.1700	0.1450	0.233	0.1200	0.197
8	0.1720	0.1470	0.238	0.1230	0.201
9	0.1740	0.1500	0.239	0.1240	0.222
10	0.1770	0.1590	0.245	0.1300	0.225
11	0.1790	0.1610	0.246	0.1330	0.229
12	0.1800	0.1650	0.247	0.1350	0.231
13	0.1810	0.1700	0.247	0.1540	0.240
14	0.1900	0.1710	0.248	0.1630	0.243
15	0.2000	0.1720	0.249	0.1640	0.244
16	0.2100	0.2010	0.250	0.1730	0.249
17	0.2570	0.2120	0.251	0.1740	0.250
18	0.890	0.2200	0.252	0.1830	0.255
19	x	0.2220	0.262	0.1930	0.424
20	x	0.2300	0.265	0.1920	0.515
21	x	0.2520	0.267	0.1910	x
22	x	0.2610	0.272	0.2220	x
23	x	0.2890	0.318	0.2400	x
24	x	0.3090	0.617	0.4210	x
25	x	0.3580	x	x	x
26	x	x			

No.	Ex 6	Ex 7	Ex 8	Ex 9	Ex 10
1	0.059	0.078	0.115	0.088	0.097
2	0.061	0.083	0.125	0.097	0.107
3	0.070	0.086	0.126	0.116	0.117
4	0.096	0.088	0.127	0.118	0.119
5	0.106	0.093	0.128	0.121	0.122
6	0.114	0.098	0.130	0.124	0.125
7	0.115	0.112	0.131	0.128	0.129
8	0.118	0.115	0.134	0.129	0.130
9	0.120	0.117	0.135	0.131	0.132
10	0.123	0.136	0.137	0.133	0.133
11	0.125	0.142	0.138	0.134	0.134
12	0.126	0.148	0.142	0.135	0.137
13	0.129	0.155	0.144	0.155	0.139
14	0.130	0.160	0.149	0.164	0.142
15	0.133	0.166	0.152	0.192	0.144
16	0.134	0.169	0.153	0.806	0.143
17	0.135	0.170	0.155	x	0.145
18	0.144	0.172	0.169	x	0.170
19	0.146	0.174	0.170	x	0.194
20	0.150	0.175	0.172	x	0.202
21	0.151	0.182	0.174	x	0.211
22	0.154	0.200	0.222	x	0.212
23	0.163	0.222	0.230	x	0.270
24	0.428	0.250	0.239	x	0.280
25	x	0.586	0.242	x	x
26	x	x	0.511	x	x

The relationship between TW and CF components over time and Lc is shown specifically through the graphs of each respective experiment (Ex). These graphs are introduced from Figure 5 to 14.

Comparing Ex1 and Ex2 (Figure 5 and Figure 6), the cutting speed, depth of cut remains unchanged and the feed rate increases. Conspicuously, the number of cuts increased (from 18 to 25 turns), the machining time increased and the value of the cutting force increased. The cutting tool is destroyed in Ex1 but not in Ex2 although the machining time in Ex2 is much longer than in Ex1. This shows that the cutting speed and feed speed have a great influence on the cutting force and tool life.

Experiment 1:

$$V_c = 170(m / \min); s = 0.07(mm / rev); a_p = 0.1(mm)$$

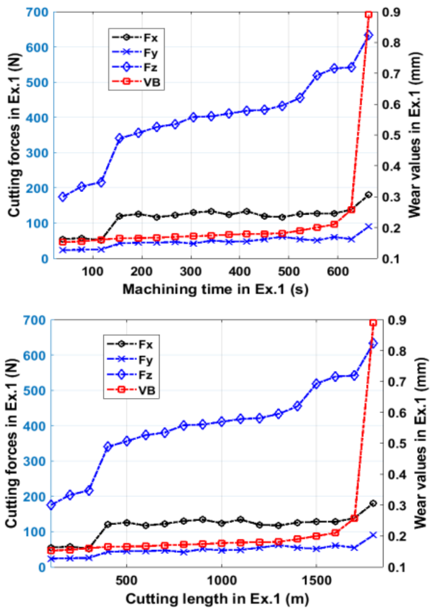


Figure 5. *Cutting force and tool wear at Ex1*

Experiment 2:

$$V_c = 125(m / \min); s = 0.11(mm / rev); a_p = 0.1(mm)$$

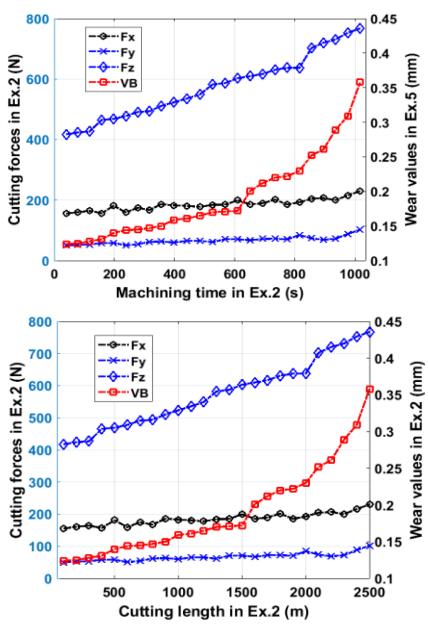


Figure 6. *Cutting force and tool wear at Ex2*

However, in Ex2 and Ex3 (Figure 6 and Figure 7) with similar machining conditions but at a higher feedrate than Ex1, the number of cuts increased sharply (25 turns and 24 turns) and Ex2 could still continue machining. This means increased tool life.

Experiment 3:

$$V_c = 170(m / \min); s = 0.11(mm / rev); a_p = 0.1(mm)$$

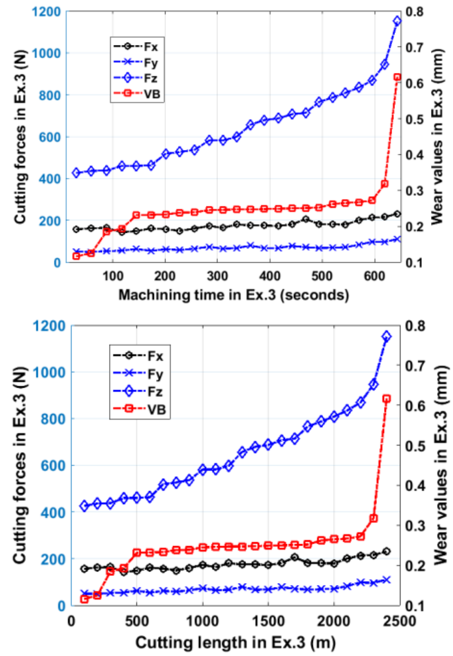


Figure 7. *Cutting force and tool wear at Ex3*

Comparing between Ex1, Ex2 and Ex3, the feed speed increases, depth of cut and cutting speed are unchanged, the number of cuts increases from 18 to 24 turns (pair Ex 1-3), the corresponding machining time increases. This means that the tool life increases. In both cases, the cutting force increases proportionally with the increase of the tool wear value. When the feed speed is small, the tool breakage occurs. Obviously, increasing and decreasing the feed rate affects the cutting force and vibration, which in turn affects the tool wear.

Experiment 4:

$$V_c = 80(m / \min); s = 0.07(mm / rev); a_p = 0.175(mm)$$

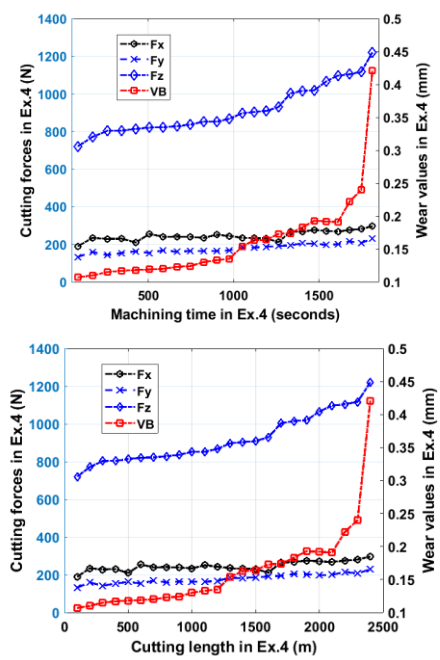


Figure 8. *Cutting force and tool wear at Ex4*

Experiment 5:

$$V_c = 80(m/\min); s = 0.1(mm/rev); a_p = 0.175(mm)$$

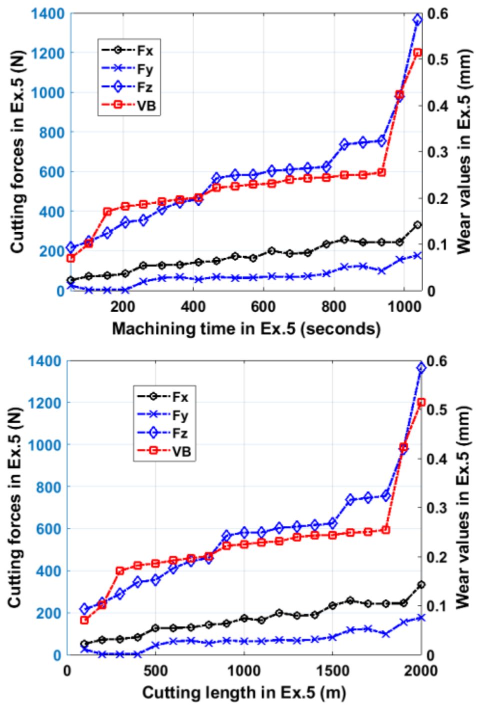


Figure 9. *Cutting force and tool wear at Ex5*

The Ex4 and Ex5 kept the same cutting speed and depth of cut, the feed speed changed from $s = 0.07(mm/rev)$ to $s = 0.1(mm/rev)$, both experiments were broken with more than 20 cuts. However, the value of CF at the first turns has a big difference, the other force values are not too different and increase steadily with time and cutting length.

Experiment 6:

$$V_c = 125(m/\min); s = 0.11(mm/rev); a_p = 0.175(mm)$$

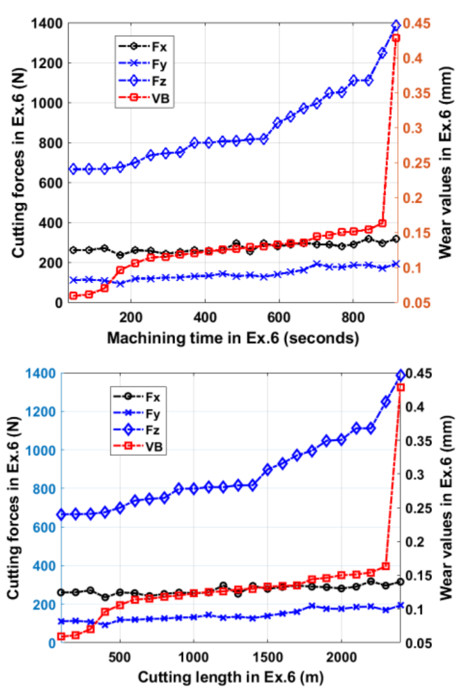


Figure 10. *Cutting force and tool wear at Ex6*

Experiment 7:

$$V_c = 80(m/\min); s = 0.07(mm/rev); a_p = 0.25(mm)$$

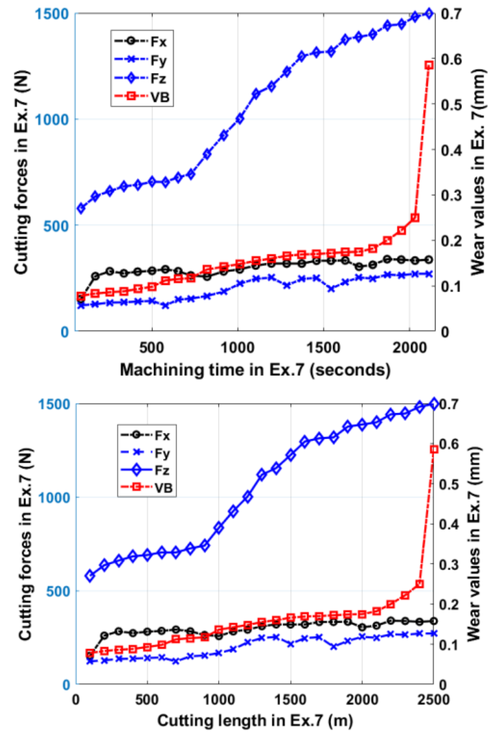


Figure 11. *Cutting force and tool wear at Ex7*

TN6 has tool breakage. This may be due to vibration or material homogeneity between the workpieces at times of testing. The Ex5 and Ex7 pairs give the same results, but a break occurs when the number of cuts exceeds 20.

Experiment 8:

$$V_c = 125(m/\min); s = 0.07(mm/rev); a_p = 0.25(mm)$$

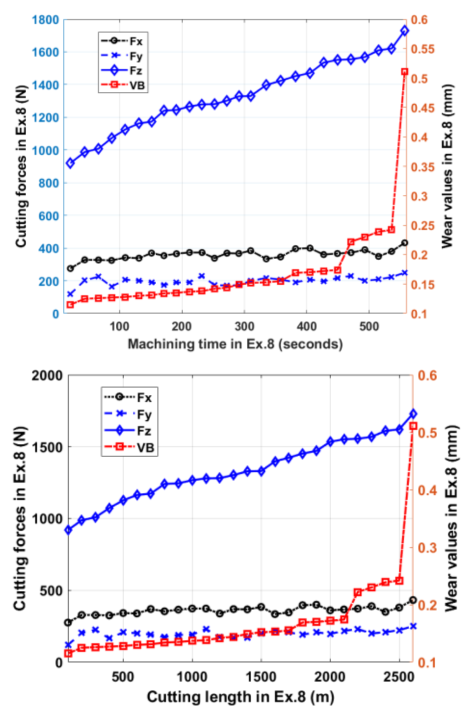


Figure 12. *Cutting force and tool wear at Ex8*

Points to note in Ex8 and Ex9, with large depth of cut and high cutting speed but small feedrate, the number of cuts is sharply reduced, especially in Ex9 (16 cuts), the machining time is low and broken quick tool. This means that the tool life is drastically reduced along with a large cutting force.

Experiment 9:

$$V_c = 170(m/\min); s = 0.07(mm/rev); a_p = 0.25(mm)$$

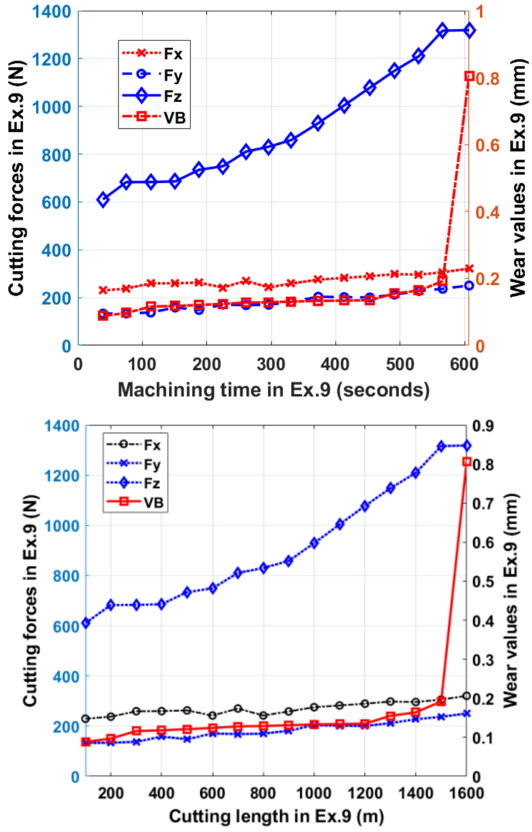


Figure 13. Cutting force and tool wear at Ex9

Comparison of Ex2 (Figure 6), Ex6 (Figure 10) and Ex10 (Figure 14) with increased depth of cut value (increased from 0.1mm, 0.175mm and 0.25mm respectively), cutting speed and feedrate not change ($125(m/\min)$ and $0.11(mm/rev)$), it is found that the number of cuts is very high (25, 24 and 24 turns), accordingly the tool life increases. It is easy to see that, with the increase of cutting depth, the cutting force increases very strongly (the largest radial force is 767N; 1384N and 1149N respectively) but the wear increases steadily but not high.

Experiment 10:

$$V_c = 125(m/\min); s = 0.11(mm/rev); a_p = 0.25(mm)$$

It should be noted that the wear value in most of the experiments spiked at the end of the survey period. This represents the time when the cutting tool has a wear value that exceeds the initial allowable value of 0.6 (mm). In the last cuts, the tool wear value is accumulated and when the tool durability limit is exceeded due to friction, cutting force, cutting heat, vibration, the tool is brocken.

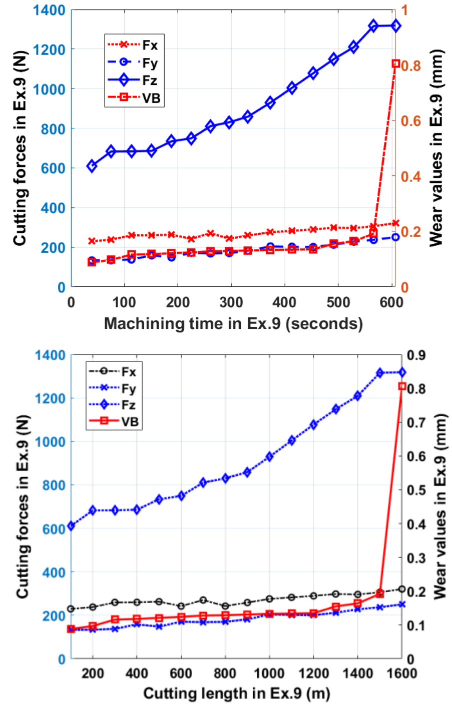


Figure 14. Cutting force and tool wear at Ex10

3. Conclusion

In general, the relationship between cutting force and flank wear of the cutting tool when turning hard and dry for SKD11 steel after heat treatment has been investigated in this paper. Experimental results are analyzed based on carefully collecting cutting force signals and measuring tool wear through modern and reliable measuring devices. Some key statements about this relationship can be described as follows:

• The value of tangential cutting force has the largest value among the components of the cutting force and this value is directly proportional to the wear of the cutting tool.

• All three cutting parameters affect cutting force, tool wear through factors such as number of cuts, cutting length and machining time.

• High cutting speed with large cutting depth results in shorter machining time (due to low number of cuts), and reduced tool life.

• Small feedrate values, small depth of cut gives small tangential cutting force values but tool breakage occurs at a certain number of machining turns.

• The increase in tool speed increases the number of machining turns, the wear increases but does not increase sharply.

• Increasing depth of cut value increases cutting force but has little effect on tool wear.

Note that these preliminary statements only consider the influence of each cutting parameter on the cutting force and tool strength. Experimental results have not specifically considered the interaction and mutual influence between cutting parameters. Obviously, this issue needs to be studied more specifically to be able to make more accurate judgments about the relationship between factors and their influence on cutting force and tool wear.

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