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Finding correlations between tool life and fundamental dry cutting tests in finishing turning of steel

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Abstract

Tool life is usually measured by end tool life tests, however, such experiments are costly and time consuming. Establishing correlation between these tests and shorter and cheaper tests is consequently of great interest. Experimental results from dry orthogonal cutting tests are reported and a good correlation between temperature reached at the tool and tool life test is shown.

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Keywords: Infrared; Temperature; Tool life machinability

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1. Introduction

In recent years, there have been great advances in the development of cutting tool materials and geometries. These advances have significantly improved the material removal rate when machining a large number of metallic materials, such as cast irons, steels, nickel-based alloys or titanium alloys.

The importance of improving tool life is evidenced by the numerous studies in the literature investigating the cutting tools developments and material machinability. Empirical evidences of these effects are usually measured by of end tool life tests. However, such experiments are time consuming and costly. Despite its obvious economic and technical importance, the ability to make general, a priori predictions about the outcome of these tests remains poor.

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The heat generation occurring during metal cutting is an important factor which affects not only the properties of machined material but also the tool life [1]. The temperature reached in the tool is an indirect measurement of this heat produced due to the high plastic deformation of the material and tool-chip and tool-work piece friction. Therefore, the tool temperature reached during the cutting process could be an important factor in determining the tool wear.

Specific cutting and feed forces are also important parameters in the cutting process [2]. The chip morphology gives empirical information that allows better understanding of the cutting process and therefore the mechanisms involved in the tool wear [3].

In order to measure the cutting tool temperature, different experimental techniques have been used in the literature such as using thermo sensitive paints [4], thermocouples [5], or metallurgical methods [6]. However, in the present work an infrared method, thermography is considered. Thermography is a well-established experimental method for studying cutting tool temperature distributions in dry conditions [7–13]. The principal advantages of this technology are that (i) it is non-intrusive, and (ii) it allows determining directly the isotherms distribution. However, thermography has some drawbacks such as (i) the difficulty to measure temperature when lubricants are employed, (ii) the equipment cost and (iii) the establishment of the appropriate methodology. The present work has been carried out in dry cutting conditions to overcome the difficulty in measuring temperatures when lubricants are employed.

The main goal of this work is to show that there is good correlation between tool temperatures in short dry orthogonal cutting tests and machinability tests; thus reducing the need for end of tool life tests.

2. Experimental Method

2.1. Materials

Three different steel alloys were used: 35CrM4, 500CrMo4 and 100Cr6. These steels were subjected to heat treatment (quenching and annealing) in order to obtain desired hardness. As result of these heat treatments five material conditions were obtained, i.e. QL H2 and QL H1 from 35CrMo4, QH H1 and QH H2 from 50CrMo4 and TH from 100Cr6 (see Table 1).

Table 1. Material list, chemical composition and heat treatment.

Material (Hardness)	Chemical Composition	Vacuum Heat treatment
QL H2 (46 HRC)	35CrMo4	Tª aus. =900 °C -4h+Q in oil and Tª temper. =460 C -5h cooled in air
QL H1 (37 HRC)	35CrMo4	Tª aus. =900 °C -4h+Q in oil and Tª temper. =180 °C -5h cooled in air
QH H1 (54 HRC)	50CrMo4	Tª aus. =850 °C -100min+Q in oil and Tª temper. =180 °C -180min cooled in air
QH H2 (47 HRC)	50CrMo4	Tª aus. =850 °C -100min+Q in oil and Tª temper.=400 °C -180min cooled in air
TH (62 HRC)	100Cr6	Tª aus. =860 °C -100min+Q in oil and Tª temper. =180 °C -180min cooled in air

2.2. Experimental procedure

Two types of tests were carried out::

a) End tool life tests in finishing turning:

Tool life tests in finishing turning were performed using a CNGA 120408S tool, with a PCBN CB 7014 cutting material, and under the following cutting conditions: cutting speed (v_c) of 160 m/min, feed rate (*f*) of 0.08 mm and depth of cut of 0.2 mm. Cutting tests were interrupted after several time intervals in order to study the tool wear phenomena. A macrosocope was used to evaluate the flank wear value.

b) Fundamental cutting test in finishing turning:

The fundamental tests employed were orthogonal dry cutting tests conducted on a Lagun vertical CNC milling machine in samples with a 1.5 mm wall thickness. CBN cutting inserts from Sandvik, (TGCW110204 S01020F 7025) were employed (Fig. 1). The cutting edge has a chamfer of 0.1mm and 30º of inclination.

In order to compare the behavior of the different steels the tests were performed at unique cutting conditions: a cutting speed of 150 m/min and a feed rate of 0.1 mm. All tests were conducted with 5 s duration and were carried out 3 times to estimate the repeatability

Table 2. . Orthogonal dry cutting tests characteristics.

Cutting speed (vc)	Feed rate (f)	Wall thickness	Rake angle	Clearance Angle	Cutting insert	Tool holder
150 m/min	0.1 mm	1.5 mm	0	7	TGCW110204 S01020F 7025	STGCL 1616 H11

During the fine machining tests, the tool temperature, cutting and feed forces were measured. To measure forces, a 3-component dynamometer (Kistler 9121) was placed under the tool holder to record the dynamic changes in the cutting forces throughout the testing. In order to ensure edge sharpness, a new tool insert was used in each test.

Fig. 1. Tools and work-pieces samples used in dry orthogonal cutting tests.

As it is shown in Fig. 2, a micro thermal imaging system comprising of a FLIR Titanium 550 M infrared camera and a microscopic lens offering a resolution of 10 µm were used to measure tool's temperatures during the orthogonal cutting of all alloys on the cutting edge.

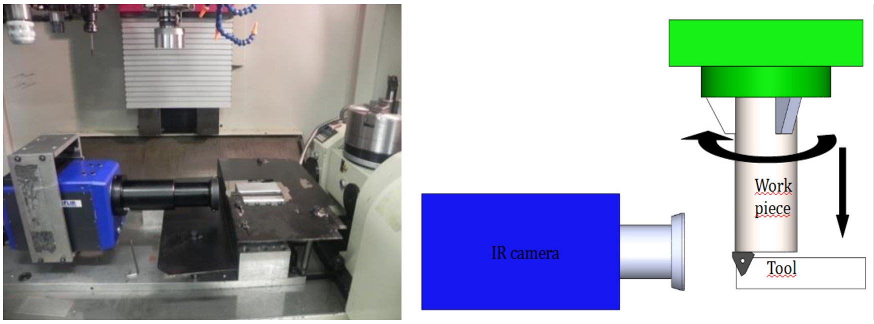


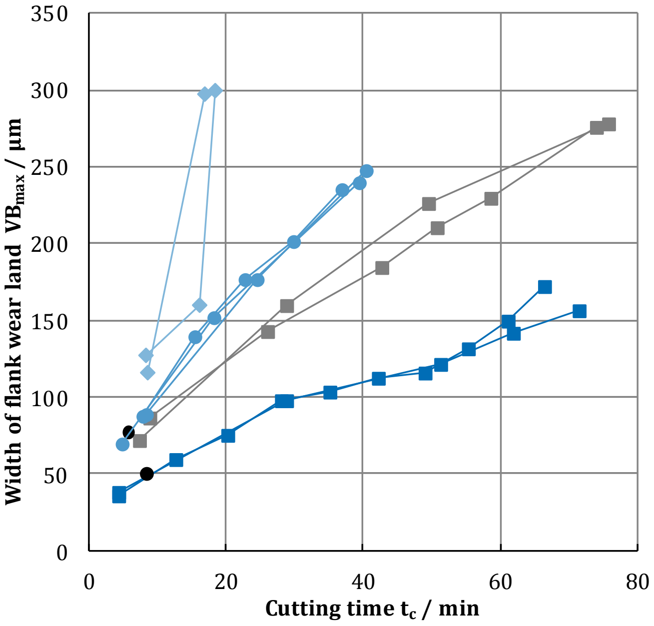
Fig. 2. Experimental setup of fundamental cutting test in finishing turning.

A high-speed, high-resolution digital filming system (HHF), PHOTRON FASTCAM-ULTIMA APX-RS 250K MONOCHROME, was also employed with a frame rate of 2500 Hz, to analyze the average chip thickness, the shear angle and the chip shape (segmented or serrated, continuous).

3. Experimental Results

3.1. Tool life tests in finishing turning

Fig. 3 shows the results obtained for tool life tests in finishing turning. As it can be observed, few data appears for QL-H1 steel alloy because the tests were finished before reaching the VB_{max} higher than 100 µm, as a consequence of the bad surface roughness when machining this alloy.



Process: External turning

Cutting parameters:
v_c = 160 m/min
f = 0.08 mm
a_p = 0.2 mm

Material:
QH-H1 50CrMo4 (59 HRC), induction hardened
QH-H2 50CrMo4 (41 HRC)
B-H1 100Cr6 (55 HRC)
QL-H1 35CrMo4 (30 HRC)
QL-H2 35CrMo4 (45 HRC)

Coolant: Dry

Cutting material: PCBN

Tool geometry: CNGA120408S

Fig. 3. Results of tool life test in finishing turning performed at the following cutting conditions: v_c = 160 m/min; feed f = 0.08 mm; depth of cut ap = 0.2 mm.

3.2. Specific Cutting and Feed forces

Average values for specific cutting forces (K_c) and specific feed forces (K_f) are shown in Fig. 4 and Fig. 5 respectively. The average uncertainty for specific cutting forces is 60 N/mm^2 while for the specific feed force is 112 N/mm^2.

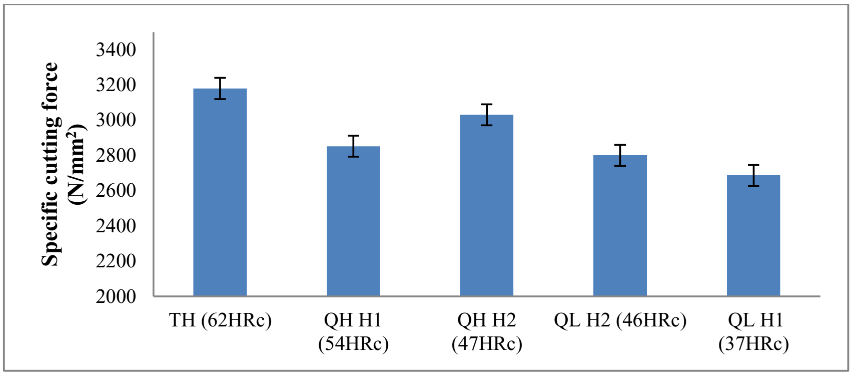


Fig. 4. Specific cutting force results (v_c = 150 m/min, f = 0.1 mm).

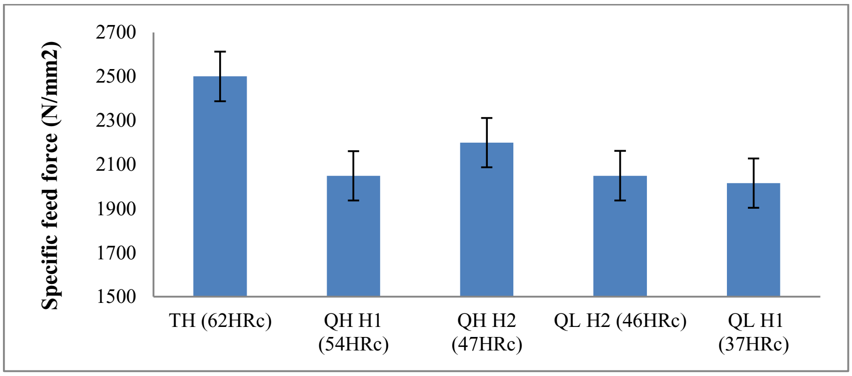
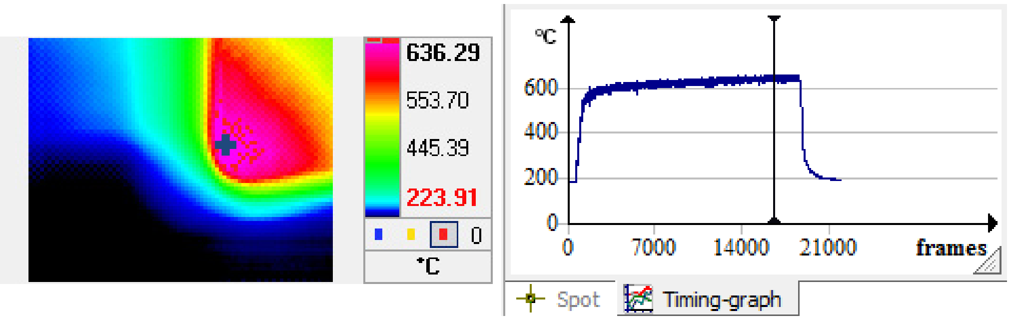


Fig. 5. Specific feed force results (v_c = 150 m/min, f = 0.1 mm)

3.3. Tool temperature

Tool temperature values were recorded during 5 seconds. However, values obtained for the last 28 ms of the cutting process, that is when the steady state conditions were nearly reached, were considered in the study. Fig. 6a shows an image of the cutting tool and a graph (Fig. 6b) of the temperature trend of a given point (highlighted in Fig. 6a).



a) b)

Fig. 6. Temperature reached at the tool during the cutting of QH-H1 alloy (v_c = 150 m/min, f = 0.1 mm)

Fig. 7 shows the cutting tool temperature for all the analyzed steel alloys. The temperature shown in the figure corresponds to the average temperature of a slim strip of 300x10 μm^2 over the rake face. This temperature is calculated assuming a constant emissivity of 0.9 [14], and the uncertainty is estimated to be about 10 %. More details about the way to estimate uncertainty value can be found in [15].

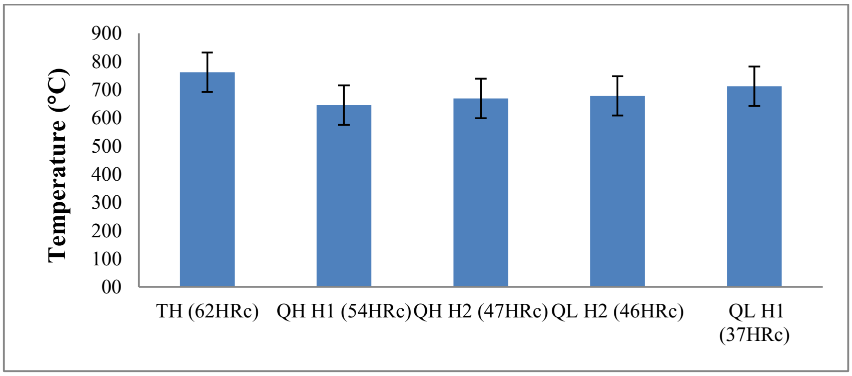
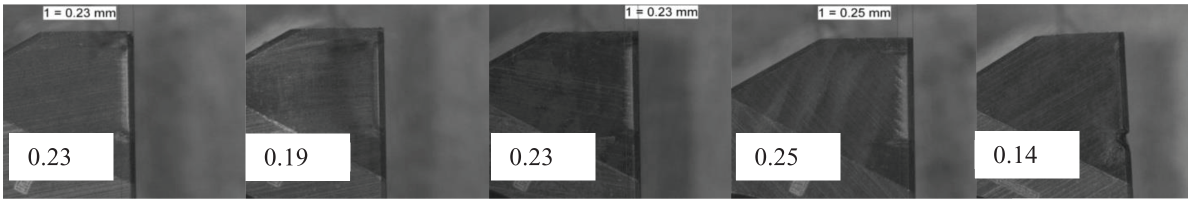


Fig. 7. Temperature reached at the tool during a dry orthogonal cutting (v_c = 150 m/min, f = 0.1 mm)

3.4. Tool chip contact

Tool chip contact length was measured for each test. A macroscope was used to observe the tool chip contact length. The uncertainty of contact length is estimated to be about 0.02 mm. Fig. 8 shows the tool rake surface after machining tested materials. Values obtained for each test are presented in Table 3

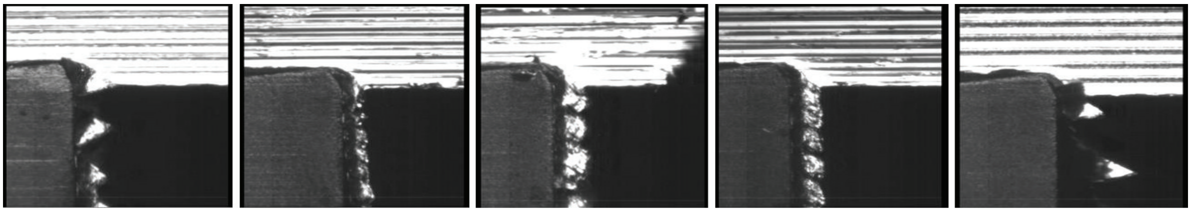


a) b) c d) e)

Fig. 8. Tool wear of the tool after machining a) QH-H1 alloy, b) QH-H2, c) QL-H1, d) QL-H2 and e) TH

3.5. Chip thickness and morphology

HHF was performed to observe the chip formation and thus the chip shape. Fig. 9 shows a frame of the film obtained for every steel. It can be observed that QH-H1 (a) and TH (d) have a serrated chip, while QH-H2 (b) and QL-H2(d) have a continuous chip. QL-H1 alloy exhibits during the cut both chip shape, serrated and continuous. Results about average chip thickness in Table 3.



a) b) c) d) e)

Fig. 9. A frame of HHF when machining a) QH-H1 alloy, b) QH-H2, c) QL-H1, d) QL-H2 and e) TH

Table 3. summarizes all the information obtained in the experimental results.

Material	Tool-life Ranking	Hard. (HRc)	Kc (N/mm2)	Kf (N/ mm2)	Temp. (°C)	Contact Length (mm)	Chip Thickness (%)	Chip shape
QH H1	1 (65 min)	54	2853	2050	645	0.23	108	Serrated
QH H2	2 (27 min)	47	3031	2200	669	0.19	104	Continuous
QL H2	3-4 (19 min)	46	2801	2050	678	0.23	143	Continuous
QL H1	3-4 (19 min)	37	2687	2015	712	0.25	142	Cont. and serrated
TH	5 (16 min)	62	3180	2500	762	0.14	56	Serrated

4. Discussion

After Fig. 3, and considering the cutting time needed to reach a VB_{max} of 150 µm or a maximum roughness of 0.8 µm it is possible to establish a machinability ranking of different alloys, being the QH-H1 alloy the best and the TH alloy the worst.

As it can be seen in Table 3, there is a good correlation between tool temperature and tool life ranking. However, no clear correlation between other parameters and machinability tests can be deduced from these tests.

As for the tool temperatures reached when cutting QH-H2 and QL-H2 alloys, it could be observed that have similar temperature (Table 3). This fact suggests that for these steels, the hardness achieved is more relevant than the material composition.

Surprisingly, the tool temperature in QL and QH steels decreases as the hardness increases. This can be observed when comparing QL-H1 with QL-H2 and QH-H1 with QH-H2 in table 3. Not clear reasons have been found for this behavior.

Although it was expected to find a high correlation between the hardness and the specific cutting forces, QH-H1 (54HRc) steel does not follow this correlation. That is, being the second harder material, the specific cutting force (K_c) of this steel is in the third position and the specific feed force (Kf) is in the fourth-fifth position, as it could be observed in Fig. 3 and Fig. 4, respectively.

As for the chip thickness and tool-chip contact length, no clear relationship between these parameters and other such as tool life ranking, temperature or cutting and feed forces is either observed.

5. Conclusions

The main conclusions obtained after the experimental tests are the following:

- There is good correlation between the tool temperature achieved by the tool in short dry orthogonal cutting tests of several steels and the corresponding tool life tests in finishing turning; therefore, tool temperature measurement seems to be useful for establishing machinability rankings.
- There is not experimental evidence that higher hardness implies worse machinability. Moreover, when a single material is considered, it has been observed that the hardest has better result in a machinability test.
- As general trend, increasing the hardness of the work pieces increases the cutting forces
- No clear correlation is observed between specific forces, chip thickness, tool-chip contact length and tool temperatures. Thus more detailed analysis is needed to understand the complexity of chip formation process.

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