Experimental and Numerical Investigation of Temperature Distribution in the Cutting Zone with Different Coated Tools in Orthogonal Turning Operations

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Abstract. In orthogonal turning operations, the mechanical energy is converted into heat. The generated heat influences tool life and wear, and the accuracy and quality of workpieces. In the current work, the temperature distribution at cutting zone was studied experimentally and numerically. The K-type thermocouple was utilized to measure the cutting zone temperature during turning process for steel AISI 1010. DEFORM-2D has been utilized to simulate the turning operation, which was carried out using many coated and uncoated carbide tools. The experimental tests were implemented at constant depth of cut with different feed rates and cutting speeds. The results of numerical and experimental tests are illustrated. The influences of coated and uncoated tools, feed rate and cutting speed in temperature distribution at cutting zone are discussed, whereby the TiN/Al₂O₃/TiCN coated tool has the lowest temperature distribution at cutting zone compared to the other coated and uncoated tools, while the uncoated tool has the highest temperature distribution compared to coated cutting tools. Also, the increasing of cutting speed and feed rate led to an increase of temperature at the cutting zone.

Keywords: FEM, Temperature Distribution, Coated Tools, Orthogonal Turning.

1. Introduction

Metal cutting factories now use many types of machining, and in particular, turning processes. It is helpful to understand the influences of temperature and heat increases on the turning process. In general, the consumption of mechanical energy in the plastic deformation form is converted into heat during a turning operation. The generated heat has effects on tool life, wear and alteration of the metallurgical structure, and has an influence on the workpiece in terms of quality of surface, dimensional accuracy, oxidation, burning, etc. [1][2][3].

The distribution of temperature at the cutting zone depends on the chemical and mechanical properties of the tool and workpiece materials, tool geometry, feed rate, cutting speed, depth of cut and other parameters [4][5][6]. It is important to measure the cutting zone temperature to expedite the evacuation of chips and the preciseness of the tool-chip contact zone [2]. Many researchers have used various techniques including the embedded thermocouple, tool-chip thermocouple, radiation and thermos colors for measuring the cutting temperature at cutting zones. The technique most widely-used during machining processes is the tool-work thermocouple technique because of its low cost, ability to make many ranges of temperatures available and ease of use in comparison with other techniques [7][8][9].

Cotterell [10] developed a video analysis technique by using IR imagining to measure the temperature distribution and strain during orthogonal cutting. Heigel [11] calculated the temperature at cutting zone in the machining of titanium alloys, using transparent yttrium aluminum garnet (YAG) tools and infrared technique for several speeds of cutting. Satish [12] and Abhang [13] have utilized a tool-work thermocouple technique to measure the average temperature of the cutting zone, accounting for the influences of the coated tools and cutting parameters on steel workpieces. Kannan [14] investigated the optimal cutting
parameters for maximum surface finish and minimum cutting temperature with the response surface method (RSM) technique in turning.

Yahya [15] and Pradip [16] have established in orthogonal cutting a numerical model, by utilizing the finite element method (FEM) for determining temperature distribution. Amulya [17] tried to decrease the heat generation in a turning process via optimized parameters of cutting by use of a genetic algorithm (GA). Abdil [18], by utilizing infrared radiation (IR) pyrometer and K-type thermocouple, has shown that the most influential parameter in cutting zone temperature is the cutting speed.

Adnan [19] has chosen the optimal machining parameters containing cutting temperature in a turning process, using GA. Pedro [20], Julien [21] and Daniel [22] have modelled in orthogonal cutting the temperature of the tool – chip interface by utilizing the infrared thermography technique. Fuat [23] has predicted cutting temperatures by using an artificial neural network (ANN) optimization model in orthogonal cutting. Sadeghifar [24] has selected, for constant force of cutting and minimum temperature of cutting, the optimal parameters of machining by application of a combination of sequential quadratic programming (SQP) and GA techniques. By utilizing GA and RSM, Mandal and Tanmoy [25] optimized the cutting zone temperature for steel workpieces.

In this paper, many experimental and numerical tests were used to study the influence of different coated tools on the temperature of the cutting zone. The K-type thermocouple is a method which can be used to measure the temperature at the cutting zone. In addition to a finite element method, the DEFORM 2D package was used for numerical tests.

2. Experimental procedure and details

The technique used in the current work to measure the cutting zone temperature is the K-type thermocouple, which was selected due to the high response time and good repeatability as well as affordability.

The Seebeck effect is the principle of thermocouple work. The K-type thermocouple can measure temperatures from -200 to +1200 °C [1][26]. The set-up is shown in Figure 1.

All tests were conducted using a KORYO KIGYE lathe (1000×400) mm without any coolant. The workpiece material was steel AISI 1010 as the experiment specimen, where the shape was a hollow cylindrical bar with 48mm outer diameter and 45mm inner diameter. The chemical composition of workpiece is shown in Table 1.

In orthogonal cutting tests, TiN coated, TiN/TiCN coated, TiN/Al₂O₃/TiCN coated and uncoated (WC) cutting tools were used. The identical geometry of these inserts is designated by ANSI as CCMT 09-T304. All these inserts possess angle of rake as (0°) and the angle of clearance as (7°) as shown in Figure 2. The conditions of cutting were implemented at the cutting speed of 27, 48, 85, 121 and 151 m/min, the feed rate of 0.05, 0.075, 0.1, 0.125 and 0.15 mm/rev and the depth of cut as constant value of 1.5 mm.
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Figure 1. The thermocouple set-up

Figure 2. The carbide insert

Table 1. Chemical composition of the workpiece material

| Element | (C) | (Si) | (Mn) | (P) | (S) | (Cr) | (Ni) | (Al) | (Co) | (Cu) | (Fe) |
|---------|-----|------|------|-----|-----|------|------|------|------|------|------|
| Weight (%) | 0.085 | 0.032 | 0.532 | 0.019 | 0.006 | 0.014 | 0.03 | 0.028 | 0.003 | 0.005 | 99.24 |

3. FEM model for orthogonal turning

Recently, the finite element method (FEM) has been mainly used to simulate metal cutting operations, especially for temperature distribution at cutting zones [27]. DEFORM-2D (Design Environment for Forming) was utilized to simulate the orthogonal turning process. The created tool has dimensional properties comprising a rake angle of (0°), nose radius of (0.04) mm and clearance angle of (7°). Tool mesh generation was 700 by selecting relative mesh size. The workpiece material was AISI 1010 low carbon steel with an ambient temperature of 20° C and 1500 as workpiece mesh generation. Figure (3) shows the temperature distribution at cutting zone.
4. Results and discussion:

The orthogonal cutting tests were achieved experimentally and numerically, to compare the temperature distribution during the turning operation at coated tungsten carbide and uncoated cutting tools. Figure 4 shows that when the feed rate increased from 0.05 to 0.15 mm/rev at cutting speed 27 m/min, the cutting zone temperature increased numerically from 230°C to 282°C for the uncoated tool and from 215°C to 259°C for TiN/Al₂O₃/TiCN for coated tools. The temperature distribution of the other tools was located between these, or equal. The experimental tests resemble the numerical tests. So, the lowest temperature distribution occurred at TiN/Al₂O₃/TiCN, coated cutting tool, because Al₂O₃ has a low thermal conductivity. In contrast, the highest temperature distribution occurred with the uncoated cutting tool.

Figure 5 shows that when the feed rate increases from 0.05 to 0.15 mm/rev at cutting speed 48 m/min, the cutting zone temperature increased experimentally from 262°C to 326°C for uncoated tool and from 220°C to 308°C for TiN/Al₂O₃/TiCN for coated tool, and the temperature distribution of the other tools fell between them or was equal. The numerical tests are similar to the experimental tests. Also, the temperature distribution of the uncoated tool is higher than the other, coated, tools.

Figure 6 shows that when the feed rate increased from 0.05 to 0.15 mm/rev at cutting speed 85 m/min, the cutting zone temperature increased numerically from 340°C to 389°C for uncoated tool and from 324°C to 362°C for TiN/Al₂O₃/TiCN coated tool, and the temperature distribution of the other tools was located between them or equal. The experimental tests resemble the numerical tests. Also, the temperature distribution of the uncoated tool is higher than the coated tools.
Figure 4. Temperature-feed rate curve for v=27 m/min. a. Numerical. b. Experimental.

Figure 5. Temperature-feed rate curve for v=48 m/min. a. Numerical. b. Experimental.

Figure 6. Temperature-feed rate curve for v=85 m/min. a. Numerical. b. Experimental.

Figure 7 shows that when the feed rate increased from 0.05 to 0.15 mm/rev at cutting speed 121 m/min, the cutting zone temperature increased numerically from 377°C to 420°C for the uncoated tool and from 365°C to 398°C for TiN/Al₂O₃/TiCN coated tool, and the temperature distribution of the other
tools was located between them or equal. The experimental tests are similar to the numerical tests. Also, the temperature distribution of the uncoated tool was higher than the other, coated, tools.

Figure 8 shows that when the feed rate increased from 0.05 to 0.15 mm/rev at cutting speed 151 m/min, the cutting zone temperature increased experimentally from 333°C to 373°C for uncoated tool and from 309°C to 327°C for TiN/Al₂O₃/TiCN coated tool, and the temperature distribution of the other tools was located between them or equal. The numerical tests are similar to the experimental tests. Also, the temperature distribution of uncoated tool was higher than the other coated tools.

Figure 9 shows that when the cutting speed increased from 27 to 151 m/min at feed rate 0.05 mm/rev, the cutting zone temperature increased experimentally from 210°C to 333°C for uncoated tool and from 183°C to 309°C for TiN/Al₂O₃/TiCN coated tools, and the temperature distribution of other tools was found between them or was equal. The numerical tests resemble the experimental tests. So, the lowest temperature distribution occurred at TiN/Al₂O₃/TiCN coated cutting tool because Al₂O₃ has a low thermal conductivity, and in contrast to this, the highest temperature distribution occurred at the uncoated cutting tool.

Figure 10 shows that when the cutting speed increased from 27 to 151 m/min at feed rate 0.075 mm/rev, the cutting zone temperature increased numerically from 248°C to 416°C for the uncoated tool and from 233°C to 397°C for TiN/Al₂O₃/TiCN coated tool, and the temperature distribution of the other tools came between them or was equal. The experimental tests are similar to the numerical tests, and the temperature distribution of uncoated tool is higher than the other coated tools.
Figure 11 shows that when the cutting speed increased from 27 to 151 m/min at feed rate 0.1 mm/rev, the cutting zone temperature increased experimentally from 241°C to 355°C for uncoated tool and from 226°C to 318°C for TiN/Al₂O₃/TiCN coated tool, and the temperature distribution of the other tools was located between them or equal. The numerical tests resemble experimental tests. The temperature distribution of uncoated tool is higher than the other coated tools.

Figure 9. Temperature-cutting speed curve for f=0.05 mm/rev. a. Numerical. b. Experimental.

Figure 10. Temperature-cutting speed curve for f=0.075 mm/rev. a. Numerical. b. Experimental.

Figure 11. Temperature-cutting speed curve for f=0.1 mm/rev. a. Numerical. b. Experimental.

Figure 12 shows that when the cutting speed increased from 27 to 151 m/min at feed rate 0.125 mm/rev, the cutting zone temperature increased experimentally from 262°C to 369°C for uncoated tool and
from 236°C to 323°C for TiN/ Al₂O₃/TiCN coated tool, and the temperature distribution of the other tools is located between them or equal. The numerical tests are similar to the experimental tests. Also, the temperature distribution of the uncoated tool was higher than the other coated tools.

Figure 13 shows that when the cutting speed increased from 27 to 151 m/min at feed rate 0.15 mm/rev, the cutting zone temperature increased numerically from 282°C to 437°C for uncoated tool and from 259°C to 415°C for TiN/ Al₂O₃/TiCN coated tool, and the temperature distribution of the other tools was located between them or equal. The experimental tests are similar to the numerical tests. Also, the temperature distribution of uncoated tool was higher than the other coated tools.

It is noted that there is a difference in numerical and experimental temperature readings, for example the temperature at v=121 m/min and f=0.05 mm/rev of 317°C experimentally and of 377°C numerically. Also, for the same cutting speed and f=0.15 mm/rev the temperature of 364°C experimentally and of 420°C numerically for uncoated tool. This may be a result of the thermocouple set-up, whereby it was mounted on the bottom surface of the tool and to avoid this difference, infrared camera can be used.

5. Conclusions
In this paper, a K-type thermocouple was utilized to measure the cutting zone temperature during orthogonal turning operation on a lathe machine, using coated and uncoated cutting tools on steel AISI 1010 as workpiece material. Also, DEFORMS 2D was used for numerical tests. The paper documents the effects of coated and uncoated cutting tools, cutting speed and feed rate on the temperature distribution at the cutting zone. From numerical and experimental results, the following conclusions can be drawn:

1) It is noticed that the orthogonal cutting temperature for the uncoated tool is higher than that for coated tools, e.g. the temperature at f=0.075 mm/rev and v=85 m/min of 362°C for uncoated tool, of 347°C for TiN coated tool, of 344°C for TiN/ TiCN coated tool and of 338°C for TiN/Al₂O₃/TiCN coated tool, numerically.

2) With coated tools, it is found that the temperature of three-layer tools is lower than for the other coated tools, for example the temperature at f=0.05 mm/rev and v=151 m/min of 395°C for TiN coated tool, of 394°C for TiN/ TiCN coated tool and of 387°C for TiN/Al₂O₃/TiCN coated tool, numerically.

3) Increasing cutting speed leads to increase of the cutting zone temperature, e.g. the temperature increases from 253°C to 410°C numerically at f=0.125 mm/rev and increases v=27 to 151 m/min.

4) If there is an increase in the feed rate, there will also be increase in the cutting zone temperature. Thus, the temperature increases from 387°C to 415°C numerically at increasing f=0.05 to 0.15 mm/rev and v= 151 m/min.

5) When the cutting speed increases, the cutting zone temperature will be more affected than the feed rate.

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