Research Article

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Multilayer coating effects on the thermal conductivity of tools using an electric furnace technique**

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Abstract: This paper demonstrates the effects of multilayer coatings on the thermal conductivity of tool specimens. The experiments were conducted using copper specimens and four tool specimens with different coatings (uncoated, TiN, TiN/TiCN, and TiN/Al₂O₃/TiCN). An electrical furnace technique was used with the specimens isolated from their surroundings and temperatures measured at the contact surfaces. The specimens are joined securely, with a thermal insulator (glass wool) placed around them so that the heat flow is in the axial direction only. One surface of the copper specimen faces the heat source, and the opposite end of the tool specimen is exposed to room temperature. The experimental results displayed variations in the temperature distribution due to the effect of the coatings, and thermal conductivities were measured at temperatures ranging from 100°C to 300°C. The results indicated the optimum coating for tools (lowest thermal conductivity) of the four types is TiN/Al₂O₃/TiCN.

Keywords: Temperature measurement; thermal conductivity; multilayer coating tools

1 Introduction

The ability of a material to conduct heat, which varies from one substance to another and depends on density, area, and volume of materials, is known as thermal conductivity. When the thermal conductivity is larger, the material is a better heat conductor, whereas a low value indicates that the material has a low thermal conductance [1]. Heat conduction is a heat transfer mechanism that occurs when a temperature difference occurs between two contacting bodies [2]. Heat transfer is important for many engineering systems and affects the design and manufacture of most devices and equipment [1]. Examples include heating and cooling systems, power stations, and computers.

There are two primary techniques used to measure thermal conductivity. The first is the steady-state method, in which heat flows in only one direction, and the thermal conductivity is determined from the resulting temperature differences. The second is the transient method, which is faster than the steady-state method since the measurements are made during the heating [3]. The steady-state method is used in this paper. Thermal properties and thermal conductivity, in particular, are critical to the performance of hard coatings. For example, electrical equipment requires materials with high thermal conductivities to dissipate heat to heat sinks. Hard coatings and barrier-coated parts need low thermal conductivities to act as thermal insulation by minimizing heat transfer from the hot to the cold sides. A hard coating with low thermal conductivity is desirable as a barrier layer to minimize the temperature increase on tool substrate materials, redirect heat flow away from the chip, and disperse heat generated by the chip. This barrier layer reduces the heat transfer to metallic components and protects the tools from thermal overload [4]. Copper is extremely valuable due to its electrical and thermal conductivity, corrosion resistance, and ease of alloying [5].

Coatings have high wear resistance, high hardness and chemical stability, thus, an improvement in machining performance and tool life is attained. Two methods of carbide tool coating can be employed in use today. Both PVD and

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CVD methods are two of these technologies [6]. TiC was the first CVD tool coating for cemented carbide. CVD method and the coating materials TiCN, TiN, and Al_2O_3 were developed quickly as a result of its rapid success. PVD coating was initially employed in industry in 1980, when TiN was the first of its kind [7].

The coating system usually includes substrate, interface, and coating layers. Each of these elements influence, interactively and individually, performance under practical operating conditions. Cutting tool performance can be improved significantly depending on the properties of the coating system [8]. Material strength and thermal qualities are required by the substrate and the coating, and are determined by their composition and microstructure, as well as the porosity and homogeneity of the material [9].

Multilayer coatings consist of a series of harder and softer layers. The number of layers and the thickness of each layer influence the overall properties of the coating. The number of layers is equal to the number of interfaces, which also significantly impact coating qualities. Interfaces thicknesses range from 1 to 3 nanometers, depending on the materials in contact [10]. Multi-layer coated tools have better surface toughness and higher hardness as compared to mono-layer coated tools. Multiple coatings offer a variety of protection processes during machining various work materials because they it provides a stronger metallurgical bond between the substrate and the coating [11]. Coated carbides are primarily cemented carbide inserts that have been coated with one or more thin layers [12]. Trends toward machining of very chemically reactive and hard materials at high speeds, single or multi-layer deposition on cutting tools enables the improvement of the machining process. Coatings minimize the coefficient of friction between the chip and the cutting tool, allowing them to be used at lower temperatures as compared to uncoated inserts under equivalent cutting conditions [13].

The most common coating materials are TiN, TiC, Al_2O_3 , and TiCN, although recent developments in coating technology have developed many newer coating materials [14]. To protect cemented carbide substrates from high temperatures at the cutting edge, Al_2O_3 coatings are commonly used as thermal barriers [15]. The Al_2O_3 coating thermal conductivity decreases with increasing temperature, which is a unique feature. This makes it suited for high-speed, and high-temperature applications where a sharp edge is not a crucial consideration [16]. When compared to uncoated tools, coated tools can increase cutting speed by 30–40% (maybe up to 100%–200%) life of the tool by 200%, and capacity of cutting by 80%, making them one of the top tool solutions in high-speed cutting tools and CNC traditional machining [17].

2 Materials and methods

2.1 Conduction heat transfer

This study focuses on analyzing the heat flow and the specimens' temperatures and gradients. The conduction heat transfer rate in one dimension is given by [18]:

$$Q = K \cdot A (T_1 - T_2) / \Delta X \quad (1)$$

where Q is the heat transfer rate (W), K is the thermal conductivity ($\text{W/m} \cdot ^\circ\text{C}$), A is the area (m^2), $(T_1 - T_2)$ is the temperature difference ($^\circ\text{C}$), and ΔX is the thickness (m).

The specimens are made of different materials, as shown in Figure 1, according to Incropera [18]. The outer wall of the first specimen has a higher temperature T_1 , while the outer wall of the second specimen is at a lower temperature T_2 . The interface between the two materials is at temperature T_x . The first specimen is a standard material (copper, in this case) with known thermal conductivity K_1 and known thickness X_1 . The second specimen is the tool specimen and has unknown thermal conductivity K_2 (to be determined) and known thickness X_2 .

Figure 1: Heat flow through a double layer

The following equations were used in this study:

$$Q_1 = Q_2 \quad (2)$$

$$K_1 A_1 (T_1 - T_x) / X_1 = K_2 A_2 (T_x - T_2) / X_2 \quad (3)$$

where Q_1 is the heat transfer through first material (copper specimen), Q_2 is the heat transfer through second material (tool specimens), K_1 is the thermal conductivity of first material (copper specimen), K_2 is the thermal conductivity of second material (tool specimen), X_1 is the thickness of first material (copper specimen), and X_2 is the thickness of second specimen (tool specimen).

2.2 Thermal contact

The testing method relies on having excellent thermal contact between the specimens since the interface contact resistance is assumed to be zero. Therefore, the surfaces were made as smooth as possible, and thermal oil was applied at the interfaces to minimize the temperature drop over the contact area. The resulting interface temperature difference was considered to be nearly zero. The thermal contact conductance can be expressed by [1]:

$$h_c = Q/A \cdot \Delta T_{interface} \quad (4)$$

3 Experiments

The experimental system consists of four main components: furnace, temperature control unit, thermocouples, and a programmable logic controller (PLC) connected to a personal computer. The rectangular electrical furnace chamber has heating wires distributed on its inner side and rear walls and an installed thermocouple used for temperature monitoring. A channel designed at the furnace gate held the specimens, and thermocouples calibrated for accuracy monitored the specimen and insulation temperatures. The temperature control unit maintains the furnace at the specified temperature.

Table 1: Some specifications for different cutting tools according to the general information of Sandvik Coromant Company [19]

Inserts	Insert code	Coating compounds	Total coating thickness (μm)
H13A	uncoated	—
GC1020	TiN	2
GC1525	TiN / TiCN	3
GC4035	TiN/Al ₂ O ₃ /TiCN	12

3.1 Specimen specifications

Four commercially available tungsten-based cement carbide inserts were studied: uncoated, TiN coated, TiN/TiCN coated (TiCN inner layer and TiN outer layer), and TiN/Al₂O₃/TiCN coated (TiCN inner layer, Al₂O₃ intermediate layer, and TiN outer layer). The geometry used for all inserts was SNMM 120412. Table 1 lists the features of some specifications of coated carbide for different cutting tools according to the publishing of Sandvik Coromant Company [19].

3.2 Testing procedure

The test procedure started by setting a specified furnace temperature using the control unit. The temperature of one end of the copper specimen was established through its contact with the furnace. The furnace had a front gate opening for loading the specimens and measuring their end temperatures before being inserted into their designated slots. The copper specimen was wrapped in an insulating layer to ensure that heat flow was in the axial direction. The readings begin once the furnace had stabilized at the required temperature, which is necessary to obtain optimal temperatures along with the specimens. Once the sample was isolated correctly, it was placed in the furnace front gate opening to measure the temperatures. The specimen temperatures were recorded for furnace temperatures of 100, 150, 200, 250, and 300°C. The first reading was taken 30 minutes after the furnace reached a steady-state temperature.

3.3 Temperature measurement

Thermocouples measured the temperatures at the ends of each specimen and their interface. The role of the programmable logic control (PLC) unit is to receive the thermocouple readings and transmit them to the program running on the personal computer. Temperature readings were recorded after a steady-state condition had been reached,

Figure 2: A scheme view for the placement of specimens inside the furnace gate and the thermocouples' locations

with the specimens in tight contact due to the insulators used. We denote T_1 as the temperature of the copper specimen surface in thermal contact with the furnace, T_2 as the temperature at the interface between the two specimens, and T_3 as the temperature on the tool specimen exposed surface. All of the temperatures T_1 , T_2 , and T_3 are measured at steady-state conditions. Figure 2 indicates the placement of specimens inside the furnace gate and the locations of the thermocouples to measure the specimen temperatures.

4 Results and discussion

The thermal conductivities of the multilayer-coated tool specimens were found by applying Eq. (3) with the measured thermal conductivities are provided in Table 2.

Figure 3 shows the thermal conductivity of the samples graphically at different temperatures. The thermal conductivity increases with temperature. Higher temperature leads to higher thermal conductivity values [20]. From Figure 3, the uncoated specimen has the best heat conduction, followed by the specimen with the TiN coating and the specimen with the TiN/TiCN coating. Because of its coating materials and lower thermal conductivity layers, the sample with the TiN/Al₂O₃/TiCN coating is the least conductive.

The experimental results are in good agreement with the results given in Table 2.

Figures 4 and 5 show the time dependence of the temperature distributions for the standard copper specimen in contact with uncoated and TiN/Al₂O₃/TiCN specimens, respectively, at a furnace temperature of 100°C. T_1 is the surface temperature of the copper specimen where it contacts the heat source (furnace), T_2 is the temperature at the interface between the two specimens, and T_3 is the surface temperature of the tool specimen where it is exposed to the surroundings. These results show that the specimen

Figure 3: The relationship between the thermal conductivity and the temperature for different tool specimens

Table 2: Experimental results for the measurement of thermal conductivity of specimens

Coating compounds	The value of the thermal conductivity (k) (W/m·°C) of specimens at different temperature				
	100°C	150°C	200°C	250°C	300°C
Uncoated	1227	1324	1389	1463	1594
TiN	1051	1118	1212	1259	1358
TiN/TiCN	962	1034	1125	1178	1275
TiN/Al ₂ O ₃ /TiCN	843	911	1027	1090	1180

Table 3: Experimental results at different temperatures of uncoated specimen

Furnace temperature (°C)	Time (min.)	T_1 (°C)	T_2 (°C)	T_3 (°C)	Room temperature (°C)
100	30	65	40.8	34.2	16.6
	60	74.1	52	42.1	17.2
	90	83.7	60	49.7	17.7
	120	94	71.2	58.8	18
300	30	247.7	221.6	210.1	16.8
	60	258.1	233.7	221.2	17.4
	90	265.7	243.8	230.7	17.8
	120	278	254.5	245	18.3

Table 4: Experimental results at different temperatures of (TiN/Al₂O₃/TiCN) specimen

Furnace temperature (°C)	Time (min.)	T_1 (°C)	T_2 (°C)	T_3 (°C)	Room temperature (°C)
100	30	49.1	30.4	22	16.6
	60	57.8	40.1	30.2	17.2
	90	68.1	49.7	39.8	17.7
	120	79.4	62.8	49.6	18
300	30	205.8	181.4	170.6	16.8
	60	217.9	197.6	184.8	17.4
	90	233.1	211.6	200.1	17.8
	120	243.6	227.3	218.4	18.3

Figure 4: The temperature distribution of uncoated specimen at a constant source temperature of 100°C **Figure 5:** The temperature distribution of (TiN/Al₂O₃/TiCN) specimen at a constant source temperature of 100°C

temperatures increase with increasing exposure time to the 100°C steady-state furnace temperature. The temperature difference ($T_1 - T_3$) between the copper and test specimens was 35.2°C for the uncoated specimen and 29.8°C for the TiN/Al₂O₃/TiCN specimen because the uncoated specimen

Figure 6: The temperature distribution of uncoated specimen at a constant source temperature of 300°C **Figure 7:** The temperature distribution of (TiN/Al₂O₃/TiCN) specimen at a constant source temperature of 300°C

conducts heat better than the TiN/Al₂O₃/TiCN specimen. The highest temperature of the coated tool was (82°C) lower than that of the uncoated tool [21]. The experimental results are very close to those presented in Tables 3 and 4.

Figures 6 and 7 show the temperature distributions of the copper specimens with uncoated and TiN/Al₂O₃/TiCN specimens, respectively, at a steady-state furnace tempera-

ture of 300°C. Figure 6 shows the temperature distribution with an uncoated specimen, where the measured temperatures were $T_1 = 278^\circ\text{C}$, $T_2 = 254.5^\circ\text{C}$, and $T_3 = 245^\circ\text{C}$ at 120 minutes. Figure 7 displays the results for a TiN/Al₂O₃/TiCN coated specimen where the measured temperatures were $T_1 = 243.6^\circ\text{C}$, $T_2 = 227.3^\circ\text{C}$, and $T_3 = 218.4^\circ\text{C}$ at 120 minutes. The experimental results indicate a temperature difference due to the difference in the cross-sectional area and thickness of the copper specimen. The thickness greatly affects the transfer of heat energy because it is inversely proportional to it. Note that when the thickness increases, the heat energy transfer through the material decreases [20]. These differences either enhance or reduce the heat transfer because of the heat loss to the surroundings by natural convection. The experimental results are very close to those presented in Tables 3 and 4.

These figures illustrate that TiN/Al₂O₃/TiCN produces the lowest temperatures compared to the other three coatings. Multilayer coated tools reduce the heat transfer because of the thermal insulation provided by the coating. The T_1 temperatures of the coated TiN/Al₂O₃/TiCN, TiN/TiCN, and TiN specimens are less than the uncoated specimen by about 34.4, 23.2, and 11.3°C, respectively, at a steady-state furnace temperature of 300°C. Similarly, the T_3 temperatures of the coated TiN/Al₂O₃/TiCN, TiN/TiCN, and TiN specimens are lower by about 26.6, 19.7, and 12.5°C, respectively, compared with the uncoated tool specimen at a steady-state furnace temperature of 300°C.

5 Conclusions

This study has described an experiment to measure the thermal conductivity of multilayer-coated tool specimens. The thermal contact resistance between specimens resulting from air gaps was minimized using thermal oil, leading to increased thermal contact. Coating thickness strongly affects the temperature field: the greater the thickness, the lower the temperature. Compared to the other three tool specimens, the TiN/Al₂O₃/TiCN coated specimen had the lowest temperatures, and the heat transfer was reduced due to the insulating effect of the coated layers. Experimental results showed that the thermal conductivity of the uncoated specimens is greater than the TiN/Al₂O₃/TiCN, TiN/TiCN, and TiN tool specimens by 34%, 25%, and 17%, respectively.

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