Experimental and FEM Study of Coated Inserts on cutting forces in orthogonal Cutting

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ABSTRACT

In this study, an attempt has been made to investigate and simulate the influence of coated layers, on the cutting force components in orthogonal turning process using AISI 1010 steel. A series of experimental and numerical tests have been done with four types of inserts including uncoated, coated tool with (TiN), (TiN /TiCN) and (TiN /Al$_2$O$_3$/ TiCN) using the special FEA code (DEFORM-2D). The turning tests were conducted at five different cutting speeds (45, 65, 97, 145, and 206 m/min.), while feed rate and depth of cut were kept constant at (0.2 mm/rev.) and (1.2 mm) respectively.

The results show that the minimum force is achieved when using TiN/TiCN insert compared with other inserts in all cutting conditions. The cutting force components (tangential and feed force) are decreased by (22% and 69% respectively) when the cutting speed increases from (45 to 206) m/min. The maximum relative difference between simulated and measured values is less than (17%).

Keywords: Orthogonal cutting, Finite element simulation, Multilayer coated tool**,** cutting forces.

دراسة عملية وتحليلية بطريقة العناصر المحددة لتأثير طبقات كساء عدد القطع على قوى القطع في القطع المتعامد

الخلاصة

تضمن هذا البحث محاولة لدراسة عملية وتحليلية لمحاكاة تأثير نوع وعدد طبقات كساء عدد القطع و سرعة القطع على مركبات قوى القطع في حالة القطع المتعامد عند تشغيل صلب AISI 1010. تم اجراء مجموعة من التجارب العملية والتحليلية لاربعة انواع من لقم عدد القطع غير المكسية منها والمكسية بطبقة واحدة من (TiN) و طبقتين (TiN/TiCN) وثلاث طبقات كساء (TiN/Al$_2$O$_3$/TiCN). تم اختيار خمسة قيم لسرعة القطع متمثلة بـ(45,65,97,145 and 206 m/min.) في حين تم تثبيت قيمة معدل التغذية و عمق القطع 0.2 (mm/rev. 1.2mm) على التوالي لجميع التجارب.

اظهرت النتائج بأن اقل قيمة لقوى القطع تم استحصالها عند التشغيل باستخدام عدة قطع مكسية بطبقتين (TiN/TiCN) وذلك تحت جميع ظروف القطع المذكورة اعلاه. في حالة زيادة سرعة القطع من (45m/min الى .200m/min) تقل قوة القطع بمركبتيها (المماسية وقوة التغذية) بمقدار (22%،69%) على

التوالي . كما اظهرت النتائج النهائية وجود تطابق كبير للقيم العملية مع القيم التحليلية بنسبة خطأ لا تتجاوز
. (17%)

INTRODUCTION

Metal cutting processes are widely used to remove unwanted material and achieve dimensional accuracy and desired surface finish of engineering components. It is a complex physical phenomenon which involves elastic and plastic deformation, intense friction and heat, chip formation and cutting tool wear. In order to effect cutting action, the cutting tool is forced against the workpiece and is moved relative to the workpiece. As the result, the workpiece is initially deformed elastically and when the workpiece's yield strength is exceeded plastic deformation occurs. Plastic deformation leads to chip formation, the formed chip leaves the workpiece through the cutting tool rake face [1]. One of the important cutting tool improvement in recent years has been the introduction of hard surface coatings on the substrates such as carbides. Hard coatings such as TiN, TiC, TiCN and Al_2O_3 have been used and claimed to significantly improve the tool-life, enabling components to be machined at higher 'economic' speeds. It has also been claimed that such coatings reduce the forces and power due to lower friction coefficients on the rake face [2].

A large number of experimental investigates and numerical simulations have been conducted to understand the effect of coating materials on cutting forces, **K.H.W.Seah** et al (1995), [3] evaluated the performance of various coatings on different tool substrates. All the machining tests were performed at dry condition on Rochling T-4 medium carbon steel workpiece material using various uncoated, as well as single and multilayer coated cermet and tungsten carbide inserts. A kistler type 9121 piezoelectric three – component dynamometer mounted on the (OKUMA LH 35-N 22 KW) CNC lathe was used in the turning experiments. Three different cutting speeds (150,212 and 300 m/min) and three different feed rates (0.06, 0.12 and 0.25 mm/rev.) while depth of cut was fixed at (2 mm). The results showed that for carbide tools, the cutting forces increase significantly when cutting speed is raised from 150 m/min to 212 m/min. However, for the cermet tools, the cutting forces hardly increase at all even at a high cutting speed of 300 m/min. Also the cermet tools generally produce lower cutting forces than carbide tools. **J.Wang** (2000),[4] investigated the effects of multiple layer hard surface coatings of cutting tools on cutting forces in steel turning for different commercially available carbide inserts and tool geometries over a range of cutting conditions. The machining experiments were conducted on a Takisawa TSL-1000 lathe turning a CS1020 bright mild steel bar using Kistler type 9257A three component piezoelectric dynamometer. Three levels of feed rates (0.13, 0.17and 0.21 mm/rev.) and three levels of depth of cut (0.5, 1.0 and 2.0 mm) were tested under two levels of cutting speed (108 and 206 m/min). Four different inserts of two different geometries identified by the types of SCMT and CNMM were selected and mounted on the SSBCR 2020 k12 and PCLNR 2020 k12 tool holders, which were supplied by Sandvik Company. For each geometry, uncoated as well as CVD triple coated inserts with TiC/Al2O3/TiN (TiN being the top coating layer) of totally 8 μm were used. The results showed that the percentage deviations of the cutting forces with coated and uncoated CNMM type inserts increase about 7% - 25% when the feed rate changes from (0.13 to 0.21) mm/rev., while decrease about 17%-13.6% when the cutting speed increases from (108 to 206) m/min.

The results also showed that the cutting forces of the SCMT type inserts are smaller than those of the CNMM inserts. **T. MacGinley and J. Monaghan** (2001), [5] studied the effect of coated and uncoated cemented carbide cutting tools on the machinability of the nickel-based superalloy Inconel 718. The simulation of an orthogonal metal cutting process was performed using FORGE2 machining simulation software. All turning tests were carried out on an URSUS225 center lathe. The cutting speed was used (20, 40) m/min while feed rate (0.24 mm/rev) and depth of cut (1 mm) remaining constant. Tool geometry of inserts was (SNMA 120408) and the insert is clamped on the tool holder model (PSSNR2020K12), the tool holder was mounted on a kistler 9263A piezoelectric tool-force dynamometer. The results showed that at the lower speed (20 m/min) the cutting forces increase relative to each other, and when using uncoated tools, the tool forces increase while when using coated tools the forces reduced by 11%. **I.Ciftci**, (2006),[6] studied the influence of cutting speed, tool coating top layer and workpiece material on the machined surface roughness and the cutting forces. The turning tests were conducted in dry turning of austenitic stainless steels (AISI 304 and AISI 316) on a (JOHNFORD- TC35) CNC turning center using Kistler 9257A three components piezoelectric dynamometer and CVD multilayer coated cemented carbide tools (CNMG 120408) at four different cutting speeds (120, 150, 180 and 210 m/min) while feed rate and depth of cut were kept constant at 0.16 mm/rev and 1 mm, respectively. The coated cutting tools used were TiC/TiCN/TiN and TiCN/TiC/Al_2O_3. He found that the cutting forces decreased by 7% when cutting speed increased from 120m/min to 150m/min. Also he found that TiC/TiCN/TiN coated cutting tools gave lower cutting forces than TiCN/TiC/Al_2O_3 coated tools. In addition , he reported that AISI 316 resulted in higher forces at all cutting speeds employed than AISI 304. **I.Ucun and K.Aslantas** (2011),[7] studied the effect of coating type on the cutting forces, tool stresses and temperatures when machining of AISI 4340 steel on a John ford-T35 CNC lathe using two types of coated (TiN/Al2O3/TiCN, Al_2O_3) and uncoated inserts with same geometry of (TNMA 160408).

A Kistler piezoelectric dynamometer model 9257B with a load amplifier connected to a computer was used for the acquisition of the cutting force (F_c) and feed force (F_f). The orthogonal cutting tests were carried out at feed rates of 0.05, 0.075, 0.1, and 0.2 mm/rev; the cutting speeds of 60, 120, 180, 240, 300 m/min while depth of cut was constant at 1 mm. The simulation of an orthogonal cutting process was performed using Deform-2D machining simulation software. The results show that the cutting force components decrease as the cutting speed increases for each cutting tool and the difference between numerical and experimental results is about 7% at cutting speed 300m/min. Also the result show that the cutting force components increase with increasing feed rate, the maximum difference between numerical and experimental results is about 18% occurring at feed rate 0.2mm/rev.

In this paper a series of experimental and numerical studies were carried out to understand the effect of number of coating layers on the cutting forces. The cutting tests and simulations of AISI 1010 steel were conducted using four types of inserts including uncoated, coated tool with (TiN), (TiN /TiCN) and (TiN /Al_2O_3/ TiCN) having same geometry.

Experimental and Numerical Work
Experimental Work

   The machining experiments were conducted on a (USOCA USK-310) CNC lathe machine as shown in Figure (1), turning a hollow cylinder of low carbon steel AISI 1010 steel. The outer and inner diameters of the workpiece are 38.5 mm and 36.1 mm respectively, therefore, the depth of cut is 1.2 mm. Tables (1, 2 and 3) show the details about the machine specifications, chemical composition and mechanical properties of the workpiece material respectively.

Table (1): Specifications of the CNC Machine [8].

Max. Spindle speed (r.p.m)	Max feed rate(mm/rev)	Max. work length(mm)	Tool turret type	Max. turning diameter (mm)	Total power (KW)
4200	1.9	700	V12	450	22
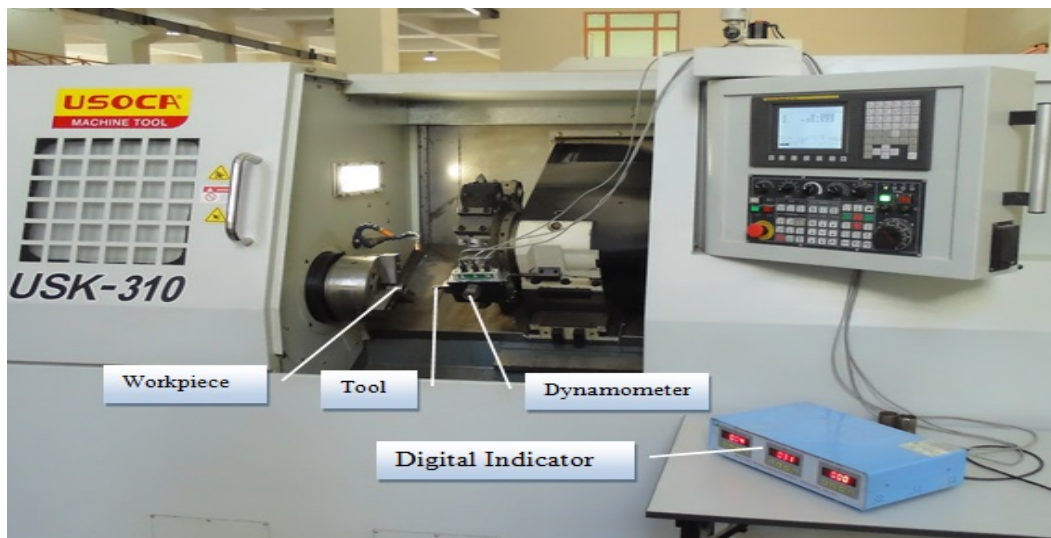
Figure (1): (USOCA USK-310) CNC lathe machine.

Table (2): Chemical composition of the workpiece material [9].

Element	(C) %	(Si) %	(Mn) %	(P) %	(S) %	(Fe) %
Weight	0.085	0.032	0.532	0.019	0.006	99.326

Table (3): Mechanical properties of the workpiece material [9].

Density (X1000kg/m^3)	7.7-8.03
Tensile Strength (Mpa)	365
Yield Strength (Mpa)	305
Poisson's Ratio	0.27-0.30
Elastic Modulus (Gpa)	190-210
Hardness (HB)	105

   The tangential and feed force components were measured using a strain gauge 3-components dynamometer (IEICOS Lathe Tool dynamometer-Model 620B:200 KgF) mounted on the CNC lathe machine and connected to a charge amplifier (IEICOS

Multicomponent Digital Force Indicator 3 channel Model 652) using display the force sensed.

Four types of commercially available tungsten based cemented carbide inserts were tested. Including: uncoated, TiN coated, TiN/TiCN coated: TiCN in the inside layer and TiN on the outside layer and TiN/Al_2O_3/TiCN coated: TiCN in the inside layer, Al_2O_3 in the middle layer and TiN on the outside layer. All the inserts had rake angle of (0°) and clearance angle of (7°) and are suitable for machining different kinds of steels at high speeds and high feed rates. All the inserts have identical geometry designated by the American National Standard Institute (ANSI) as CCMT 09T304. Table 4 summarizes the features of four cutting tools. These inserts were rigidly mounted on a right hand style tool holder which is designated by ANSI as SCLCR 1212F 09. The cutting tool inserts and tool holder assembly are shown in Figure (2).

Table (4): The features of Sandvik coromant of cutting tools [10].

| Tool Insert type	Coating compounds	Total coating thickness(μm)
H 13A	Uncoated	---
GC1020	TiN	2
GC1525	TiCN/ TiN	4
GC4035	TiCN/Al2O3/TiN	12

Figure (2): The cemented carbide inserts and tool holder used.

The turning tests were conducted at five different cutting speeds (45, 65, 97, 145, and 206 m/min.), while feed rate and depth of cut were kept constant at (0.2 mm/rev.) and (1.2 mm) respectively.

Finite Element Simulation

In this study, the Finite Element Method software being used is DEFORM-2D, which is based on Lagrangian formulation that employs implicit integration method designed for large deformation simulations with adaptive remeshing, to simulate the metal cutting process. The Finite Element model is composed of a deformable workpiece and a rigid tool which discretized by bilinear four-node quadratic. The tool penetrates through the workpiece at a constant depth of cut, variable cutting speeds

and feed rates; the finite element mesh is linked to the workpiece and follows its deformation. The modeling geometry and dimensions is done using the Cartesian coordinate 2-D model and the initial arrangement of both the workpiece and the tool in the simulation model are shown in Figure (3) [11].
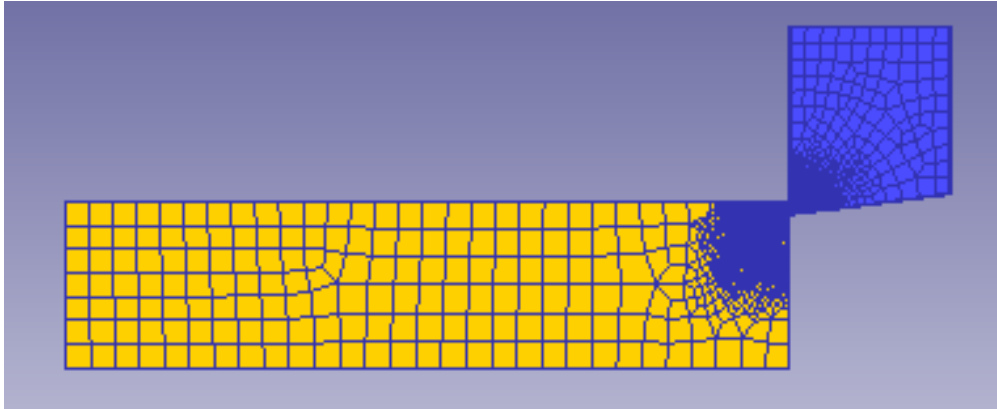
Figure (3): Setting position for the tool and workpiece in simulated tests

The FEA software has the three main parts for building a model:

• A preprocessor for creating, assembling, or modifying the data required to analyze the simulation, and for generating the required database file.
• A simulation stage for performing the numerical calculations required to analyze the process, and writing the results to the database file.
• A post-processor for reading the database file from the simulation stage and displaying the results graphically and for extracting numerical data.

Results and Discussion
Experimental Results

The effect of cutting speed on the cutting force components (tangential cutting force and feed force) was given in Figure (4a, b).When increasing the cutting speed from (45 to 206) m/min. the tangential cutting force (F_c) and feed force (F_f) is decreased by 22% and 69% respectively in all the four inserts being used at feed rate 0.2 mm/rev. the minimum force is achieved when using TiN/TiCN insert in all the cutting speeds periods, where the reduction in tangential cutting force and feed force by (19%) and (63%) respectively, this may be due to the effect of TiN/TiCN mechanical and tribology properties that generate minimum friction conditions leading to minimum cutting forces components. The percentage decrease for all inserts is:

• For uncoated tool insert the percentage reduction is (16 %) and (51%) for tangential cutting force and feed force respectively.
• For TiN coated tool insert the percentage reduction is (18 %) and (60%) for tangential cutting force and feed force respectively.
• For TiCN/Al2O3/TiN coated tool insert the percentage reduction is (17 %) and (54%) for tangential cutting force and feed force respectively.
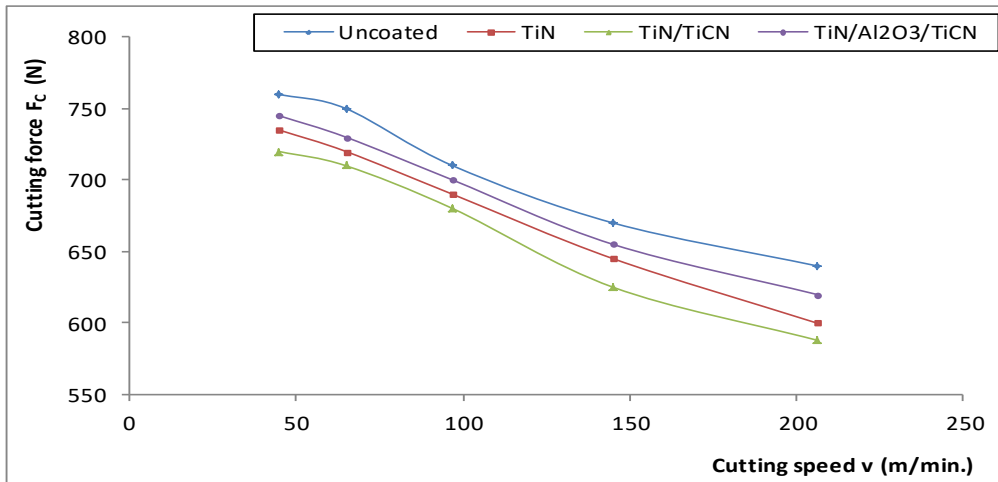
Figure (4a): Experimental results of cutting speed on tangential cutting force using different carbide inserts at f=0.2mm/rev.
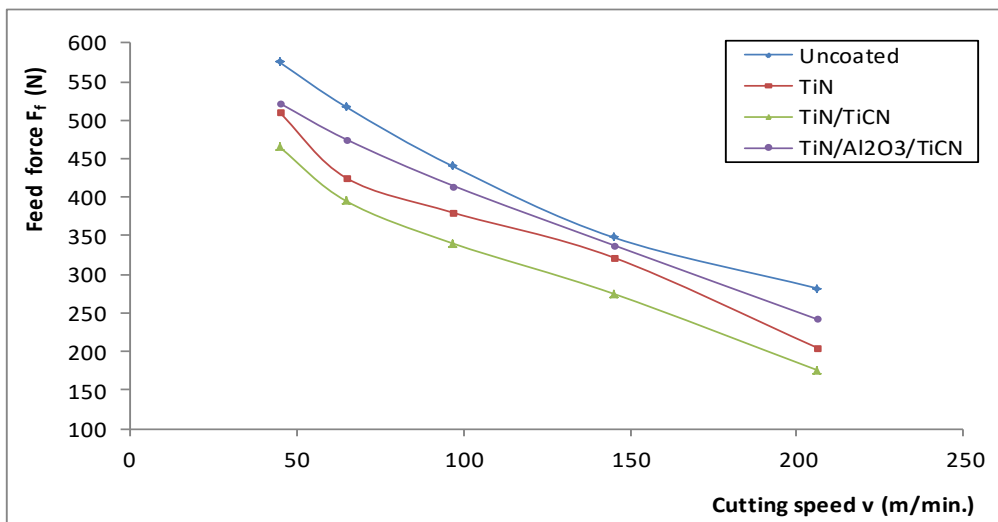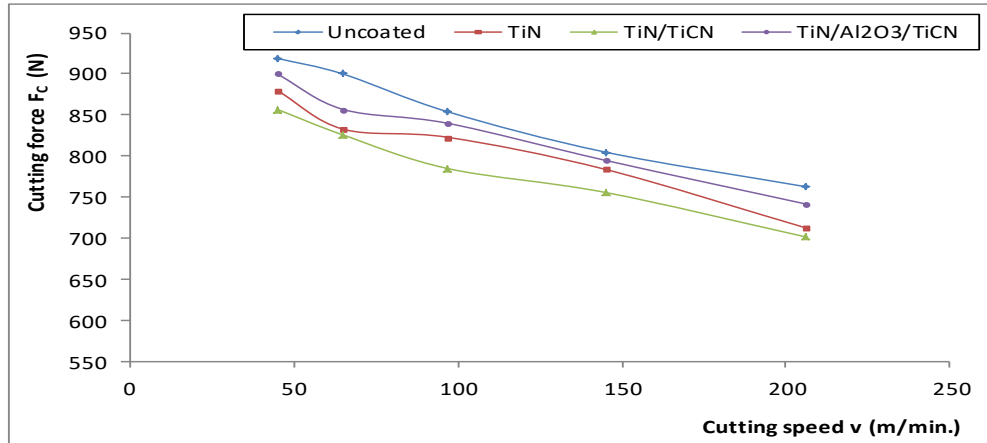

Figure (4b): Experimental results of cutting speed on feed force using different carbide inserts at f=0.2mm/rev.

Simulation Results.

From Figure (5a, b) it can be seen that numerical results show that when the cutting speed increases from (45 to 206) m/min, tangential cutting force and feed force decreased by 23% and 65% respectively for all cutting tool inserts. The minimum force is achieved when using TiN/TiCN insert in all the cutting speeds periods where the reduction in tangential cutting force and feed force is reached by 17% and 59% respectively. The percentage decrease for all inserts is:

• For uncoated tool insert the percentage reduction is (17 %) and (49%) for tangential cutting force and feed force respectively.

- For TiN coated tool insert the percentage reduction is (19 %) and (58%) for tangential cutting force and feed force respectively.
- For TiCN/Al2O3/TiN coated tool insert the percentage reduction is (17 %) and (50%) for tangential cutting force and feed force respectively.

Figure (5a): Numerical results of cutting speed on tangential cutting force using different carbide inserts at f=0.2mm/rev.
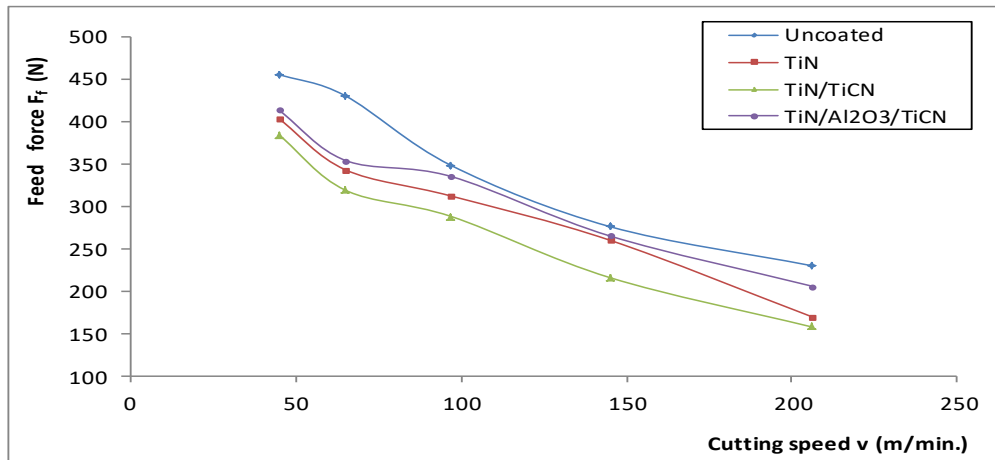
Figure (5b): Numerical results of cutting speed on feed force using different carbide inserts at f=0.2mm/rev.

CONCLUSIONS

The following conclusions can be drawn from experimental and numerical work.
1-Most numerical work gives satisfactory results compared with experimental one.
2-The cutting insert TiN/TiCN is the best in producing minimum cutting force in both tangential and feed forces.
3-The best cutting speed that gives minimum cutting force is (206 m/min).
4-The reduction percents in tangential cutting force were 7%, 4% and 2% when using TiN/TiCN insert compared to uncoated, TiN/Al$_2$O$_3$/TiCN and TiN respectively.

5-The maximum relative difference between simulated and measured values is less than (17%).

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