Finite Element Modeling and Simulation of Orthogonal Cutting With Multi Layer Coated Tools

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Abstract

This paper focuses on the development of Finite Element Method (FEM) in modeling and simulation of coated cutting tools with multi-layer coats. A special Finite Element code called (MSC.MARC mentat) is used in the numerical tests, the results are then compared with experimental work. The paper studied the effect of number of coats of cutting tools on the following field parameters; tool-chip contact length, chip contraction coefficient and shear angle at similar machining conditions.The metal being machined is (AISI 1045 steel) with orthogonal machining conditions. The three cutting tools and models are coated with (TiN, TiN/TiC, TiN/Al$_2$O$_3$/TiC), while the fourth one is uncoated.The results show good agreement between the experimental and numerical tests. Some of the results are compared with other published papers. The comparison of the predicted results shows good agreement with experimental tests with maximum relative difference of (18%) for the chip contraction coefficient and contact length, and (10 %) for the shear angle. The insert with double coats shows excellent result, compared to others from point of view of chip contraction coefficient, contact length and shear angle.

Key words: FEM, tool-chip, contact length, tool coatings, multi-layer.

الخلاصة

تم في هذا البحث دراسة تأثير عدد طبقات الطلاء لعدة القطع على كل من: معامل إنكماش النحاتة (chip contraction coefficient)، طول منطقة التماس بين وجه العدة والنحاتة(tool-chip contact length)وزاوية القص(shear angle) ، وذلك تحت متغيرات تشغيل ثابتة من سرعة قطع وعمق قطع وتغذية، حيث تضمن البحث استخدام تقنية العناصر المحددة (Finite Element Method) في نمذجة ومحاكاة النتائج والمقارنة عند تشغيل معدن صلب (AISI 1045). استخدمت ثلاثة أنواع من مواد الكساء للعدة منها: المكسية بكل من المواد التالية: (TiN و TiN/TiC و TiN/Al$_2$O$_3$/TiC) في حين كانت العدة الرابعة غير مكسية. وقد استخدم برنامج حاسوبي متخصص يدعى (MSC.MARC) في الجانب التحليلي للبحث وذلك لمقارنة النتائج التي تم التوصل اليها في الجانب العملي. أظهرت النتائج قيماً متقاربة للجانبين العملي والتحليلي كما وأظهرت كذلك توافقاً مع بعض النتائج المنشورة لباحثين آخرين في هذا المجال، وبينت النتائج بان أكبر فرق بين النتائج العملية والتحليلية لمعامل إنكماش النحاتة وطول منطقة التماس يصل إلى 18% , و 10% لزاوية القص. كما وجد بان عدة القطع المكسية بطبقتين هي المثلى من ناحية طول منطقة التماس بين وجه العدة والنحاته، زاوية القص ومعامل إنكماش النحاتة.

1-Introduction

The development of new cutting tool materials during the last few years is based mainly on sub micron hard metal substrates as well as new coatings techniques. Coatings improve wear resistance, increase tool life, broaden the application range of a given grade and enable use at higher speeds. By improving performance, coatings are

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Eugene, C. Yen, (2003)[8]applied two different methods (individual layers and composite layer)of modeling a thin multiple-layer coating system, they verified the predicted results of cutting force and chip geometry with experimental data and analyzed the temperature variation in the coating and tool substrate. **Mohamad** (2004)[9] studied experimentally the effect of coated cemented carbide tools on surface roughness and flank wear during finish turning of (AISI 1018 St.) under dry cutting conditions, the inserts tested had a coating of TiN, Al_2O_3, TiN/Al_2O_3 and TiC/Al_2O_3/TiN respectively. For comparison, uncoated cemented tungsten carbide was also tested under the same cutting conditions. The coated tools exhibited superior wear resistance over the uncoated one. The TiC/Al_2O_3/TiN coated tool had the lowest flank wear due to the high abrasive resistance of the TiC layer. The Al_2O_3 coated tool showed superior wear-resistance over the TiN/Al_2O_3 coated tool due to the TiN coating that deteriorated the effect of the Al_2O_3 outer layer. **W. Grzesik, et al** (2005)[10] checked the applicability of various simulation models to obtain Finite Element solutions of cutting forces, and other factors for a range of coated tool materials. Finite Element code (AdvantEdge) has been used in the simulation of uncoated carbide and coated P20 carbide substrates. A good agreement was achieved, especially for uncoated and three layer coated tools between predicted and experimental cutting temperatures**. Hasan**, **et al.** (2006)[11] studied experimentally the effect of number of coating materials on the surface quality of workpieces, depending on various cutting parameters in machining of (AISI 1015 St.) without cooling on a lathe using (4)different cemented carbide cutting tools, i.e. uncoated, coated with AlTiN and coated with TiAlN, and one with 3-layer coatings (outer most being TiN). In the helping cutting tool manufacturers respond to change workpiece materials and process requirements [1]. The cutting tool is the most critical part of the machining system today, approximately (85%)of carbide tools are coated, almost exclusively by the chemical vapor deposition (CVD) method [2]. Numerical methods and Finite Element modeling in particular have become increasingly popular due to the advancement in computers and the development of complex codes. Some of the models model orthogonal cutting using the Eulerian formulation. However, a majority has relied on the Lagrangian formulation, which allows the chip to be modeled from incipient to steady state [3]. The majority of inserts presently used in various metal cutting operations are cemented carbide tools coated with a material consisting of nitrides(TiN, CrN, etc.), carbides (TiC, CrC, W_2C, WC/C, etc.), oxides (e.g. Alumina Al_2O_3) or combinations of these [4,5]**. Reif** (1995) [6]studied the effect of the addition of boron (B) on surface roughness and hardness in cutting tools coated with Ti (B, N) HSS-drills and cemented carbide inserts, he compared the results with commercially available reference tools coated with TiN and (Ti,Al)N. The results of his research concluded that the hardness of the produced nitride coating increases slightly, and also a decrease in the roughness value (R_a) of the value of pure TiN with increasing boron content.**W. Grzesik** (2000)[7]made experimental investigations into the thermal interactions between the coating/substrate and the moving surface of the chip, when turning (AISI 1045 St.) in semi-orthogonal cutting, both flat-faced and grooved inserts coated with TiN,TiC/TiN,and TiC/Al_2O_3/TiN are tested. The chip contraction coefficient, contact length, and the area of contact are determined by using computer processing of scanned contact images. **Y.**

discretized by bilinear four-node quadratic.The initial geometry and mesh is presented in Figure(1) which consists of the following number of nodes and elements.

- (669) nodes and (610) elements for uncoated tool model.
- (679) nodes and (619) elements for single coated layer tool model.
- (689) nodes and (628) elements for double coated layer tool model.
- (699) nodes and (637) elements for triple coated layer tool model.

The number of nodes differ from one model to another due to the change in the coated layer number, the upper part of mesh, which constitutes the removed workpiece material, is finer, to enable the stresses, strains in the chip and tip region to be accurately distingueshed.

2-3Loading and Boundary Conditions

For the boundary conditions of our models, the nodes of the workpiece are fixed in both X and Y directions by gluing them to a rigid curve, cutting tool is moving horizontally towards - X diretion, while it is constrained in the vertical displacement. Friction is another boundary condition that could have significant consequence to the solution of the model. Due to the difficulty in measuring the friction experimentally, the values of coefficient of friction between chip and tool is assumed to be constant (μ_p=0.5) for uncoated tool, and assumed to be (μ_p=0.3) for coated tool, depending on the values found in the literatures[12, 13]

2-4 Material Properties

To ensure an accurate FE model, it is necessary that the input material properties are closely matching those of the experimental test workpiece. The workpiece material used for the plane-strain orthogonal metal cutting simulation is (AISI 1045 St.), its composition and mechanical properties are shown in tables (2&3)[13]. Therefore, tensile test specimens were made for the workpiece, by using

experiments, less average surface roughness was obtained by using a 3-layer coated tool coated outermost with TiN. The reduction of cutting speed by about (33%), will improve the surface roughness by about (26%), while when increasing the cutting speed by (310%) an improvement by (69%) in surface finish is achieved.

2-Numerical Work

In order to establish the Finite Element model, the important stages in developing the FE model are summarised as follows:

- Determination of FE appropriate model geometry.
- Generation of FE mesh.
- Application of boundary conditions and loading parameters.
- Determination of material properties.

2-1 Model Geometry

The Finite Element model is composed of a deformable workpiece and a rigid tool. The tool penetrates through the workpiece at a constant cutting speed and feed rate. The initial arrangement of both the workpiece and the tool in the simulation model are done using the Cartesian coordinate, 2-D model as shown in Fig.(1).The length of the workpiece is assumed to be (100 mm); four models are suggested, the cutting tool is modeled as multiple coating (Fig. 2- a, b&c), in order to study in detail the behavior of these layers under different conditions of layers number, the cutting conditions are assumed to be constant values as shown in (Table 1).

2-2 Mesh Generation

The Finite Element models used for the plane-strain orthogonal metal cutting simulation are based on the Lagrangian techniques and explicit dynamic, mechanical modeling software with adaptive remeshing. This means that the initial mesh becomes distorted after a certain length of cut. The workpiece for chip formation process through the Marc mentat code.

4- Experimental Tests

To imitate orthogonal metal cutting process, axial turning of the end of a tube is selected, as shown in Figure (4).

4-1 Machining Tests

M/c Type and Model: Universal center lathe SN50B is used and shown in Fig.(5),other details for the machine specifications are shown in table (6). The Chip thickness on each cutting was measured by using external micrometer having measuring range of (0 - 25 mm); scale value (0.01mm). The contact length on each cutting tool was measured by using ESE way-hardness tester, type SPVRB.2.M.

4-2 Cutting Tools Inserts

Four types of commercially available tungsten based cemented carbide inserts were tested. The cutting inserts tested were uncoated – insert 1, TiN coated – insert 2, TiN/TiC coated – insert 3 and TiN/Al2O3/TiC coated – insert 4, respectively. All the inserts 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 [CNMM 120404]. The inserts were rigidly mounted on a right hand style tool holder with a cutting rake and a back rake of (–5°). The tool holder is designated by ANSI as [PCLNR 2020 K 12].[17, 18]. The tool geometry which is used for the orthogonal and experimental tests is shown in table (7).

4-3 Workpiece Material

To achieve orthogonal cutting the experiments were done using a hollow cylinder from the end on a lathe. In this experiment, the diameter of the workpiece should be relatively larger than the depth of the cut (wall thickness of the tube) to satisfy orthogonal cutting condition. Workpiece material is (AISI (Instron 1152) servo hydraulic testing machine. Tool substrate is to be cemented carbide (WC). Table(4)[14] shows the mechanical properties of (WC), table (5)[15] shows the mechanical properties of coating layers used in the simulation tests.

3- Numerical Tests and governoring relations

The following field variables were chosen to be predicted for the simulated models at constant values of feed rate, depth of cut,cutting speed and multiple coated tools:

- **Chip Contraction Coefficient** (λ)[16]

$\lambda = t_c/t_1 = \cos(\Phi-\gamma) / \sin\Phi$ …… 1

where: t_c = deformed chip thickness (mm).

t =undeformed chip thickness (mm).

γ = rake angle.

Φ = shear angle.

- **Chip Thickness** (t_c)[16]

In practical tests, the mean chip thickness can be obtained by measuring the length and weight of a piece of chip, then

$t_c = \omega / \rho\, w\, l$ …… 2

where:

ω =weight of a piece of chip (gm).

ρ=density of work material (kg/m^3).

w = width of the chip (mm).

l = length of a piece of chip (mm).

- **Shear Angle** (Φ)[16]

$\Phi = \tan^{-1} [\cos\gamma / (\lambda - \sin\gamma)]$ … 3

- **Contact length** (Lc) for tool-chip interface region is measured directly using outside micrometer, its accuracy is 0.05mm.

The numerical tests were conducted with a Pentium 4 personal computer for the following specifications: processor 2.4 GHz.D, Ram 512 MB. The time for each Numerical test varied from (8092 to 51152 sec.) depending on number of coated layers.Fig (3) shows a representative successful simulation test in value of contact length reaching to (0.7 %). Also from the results we see that the maximum difference between contact length value from numerical and experimental work occurs at the TiN/TiC coated tool insert, that reaches (2 %). In general the results being obtained in numerical tests show greater values than experimental one within arange of (2-18 %).This phenomenon agrees well with paper being published at the literature [19].

5-3 **Effect of Coated Layers on Shear Angle (Φ)**

The relationship between the coated layers and the corresponding shear angle (Φ) is represented in Figure (8), as predicted by the Finite Element Analysis and experimental work. It can be seen that the maximum shear angle is found in the TiN/TiC coated tool insert reaching (28º) and the minimum shear angle is found in the TiN coated tool insert reaching (13º) with respect to the other tools. The maximum difference between shear angle value from numerical and experimental work reaches (6 %).

6- conclusions

The main conclusions that can be deduced from the present paper can be summarized as follows:

1. The FE software MSC Marc is successfully accomplished in modeling and simulation of our models relating to tool coating layers.
2. The chip contraction coefficient reaches maximum value of (2.9) at tools coated with three layers, and minimum value of (1.5) at tools coated with two layers.
3. The tool-chip contact length reaches maximum value of (0.36 mm) with tools coated with one layer, and minimum value of (0.27 mm) with tools coated with two layers.
4. The maximum value of shear angle is (28˚) for a tool coated with one

1045 St.) with the outer diameters of (40 mm), depth of cut was (0.5 mm). Cutting tools are made of tungsten based cemented carbide and had rake angles of (-5°) and (5°) clearance angle.

5- Discussion

5-1 Effect of Coated Layers on Chip Contraction Coefficient

The relationship between the coated layers and the corresponding chip contraction coefficient (λ) is represented in Figure (6) that shows the Finite Element Analysis, and experimental work. It can be seen that the TiN coated tool insert shows the maximum value of chip contraction coefficient with respect to other tools, while the TiN/TiC coated tool insert has the lowest chip contraction coefficient. The value of chip contraction coefficient increases from minimum value of (2.38) for TiN/TiC coated tool insert, to reach maximum value of (2.9) for TiN coated tool insert. The maximum difference between chip contraction coefficients from numerical and experimental work does not exceed (18 %). It can be concluded that the two layer coatings insert produces minimum deformation in the chip thickness resulting from many parameters relating to the TiN/TiC layer wear specifications.

5-2 **Effect of Coated Layers on Contact Length (L_c)**

It can be seen from most values in Figure (7) that, the tool insert with two layers coating has the minimum value of contact length reaching to (0.27 mm), which is the optimum one. While the ($TiN/Al_2O_3/TiC$) coated tool insert has the maximum contact length value that reaches (0.357 mm), which may be due to the existence of medium layer (Al_2O_3) that has excellent thermal- insulation properties, so that it protects the heat transfer from the chip to the tool during chip formation process. For other cases of inserts, the uncoated insert and three layer coated insert show little difference layer, and minimum value of (13°) for tools coated with two layers.

5. The maximum relative difference between simulated and measured values is less than (18%) for the contact length data and for chip contraction coefficient, less than (10%) for the shear angle value.

References

1. Kalpakjian. Schmid, Cutting Tool Materials and Cutting Fluids, Ch.21, manufacturing engineering and technology, pergamon press,1998.

2. Degarmo, E.P., Black, JT., and Kohser, R.A., Materials and processes in manufacturing, John Wiley, USA, 2003.

3. Jaton Nakia Wince, Modeling Chip Formation in Orthogonal Metal Cutting Using Finite Element Analysis, MSc. Thesis, Faculty of Mississippi State University, August 2002.

4. Armarego, E. J. A., Verezub, S., Samaranayake, P., The effect of coatings on the cutting process, friction, forces and predictive cutting models in machining operations, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, Vol. 216, pp. 347-356, 2002.

5. Cho, S. S., Komvopoulos, K., Wear Mechanisms of Multi-Layer Coated Cemented Carbide Cutting Tools, Journal of Tribology, Vol. 119, pp. 8-17, 1997.

6. A. Refit, Physical Surface Technology-PVD, FEM, 1995.

7. W.Grzesik, Thermal Characterization of the Chip-Tool Interface when using Coated Turning Inserts, Journal of Manufacturing Processes, 2000.

8. Eugene Y.C., Yen, Computer simulation of orthogonal cutting using a tool with multiple coatings, (ERC/NSM), The Ohio State University, May 2003.

9. Mohamad Nouilati, Performance Assessment of Coated Cemented Carbide Tools in Turning AISI 1018 Steel, A Thesis Submitted to the Graduate Faculty of the Louisiana State University, May 2004.

10. W.Grzesik, M. Bartoszuk, and P.Nieslony, Finite Element Modeling of Temperature Distribution in the Cutting Zone in Turning Processes with Differently Coated Tools, Journal of Materials Processing Technology, 164-165, pp. 1204-1211, 2005.

11. Hasan Gokkaya, Muammer Nalbant, The Effects of Tool Coating on the Surface Roughness of AISI 1015 Steel Depending on Cutting Parameters, Turkish J.Eng.Env. Sci., Vol.30, pp. 307-316, 2006**.**

12. Ozel,T., and Altan,T., Determination of workpiece flow stress and friction at the chip-tool contact for high-speed cutting, International Journal of Machine Tools & Manufacture, Vol.40, pp.133-152, 2000**.**

13. .Hakeem, N., Jouot, P., and Pantale, Q., A numerical simulation of steady state metal cutting**,** Proc. Inst. Mech. Eng., Vol.212, PartC, pp.331-341, 1998.

14. ISO 315, Sandvik Coromant, Introduction to metal cutting tool, HMT/MHS, 1976.

15. Eugene Y.C., Yen, Computer simulation of orthogonal cutting using a tool with multiple coatings, (ERC/NSM), The Ohio State University, May 2003.

16. Trent, E. M., Metal cutting, Butterworth-Heinemann, Oxford, 1991

17. Turning Guide, SANDVIK Coromant, 1985**.**

18. SANDVIK, Main Catalogue, 2006**.**

19. Eugene Y.C., Yen, Computer simulation of orthogonal cutting using a tool with multiple coatings, (ERC/NSM), The Ohio State University, May 2003

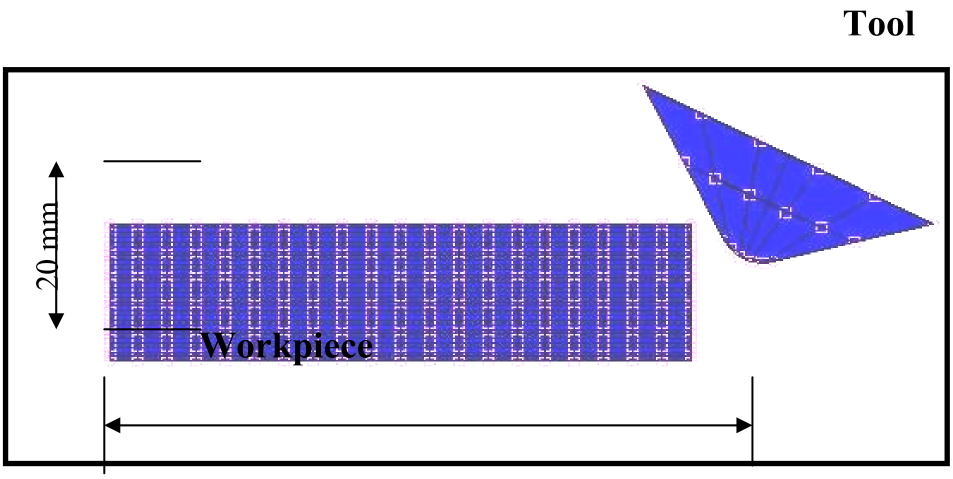
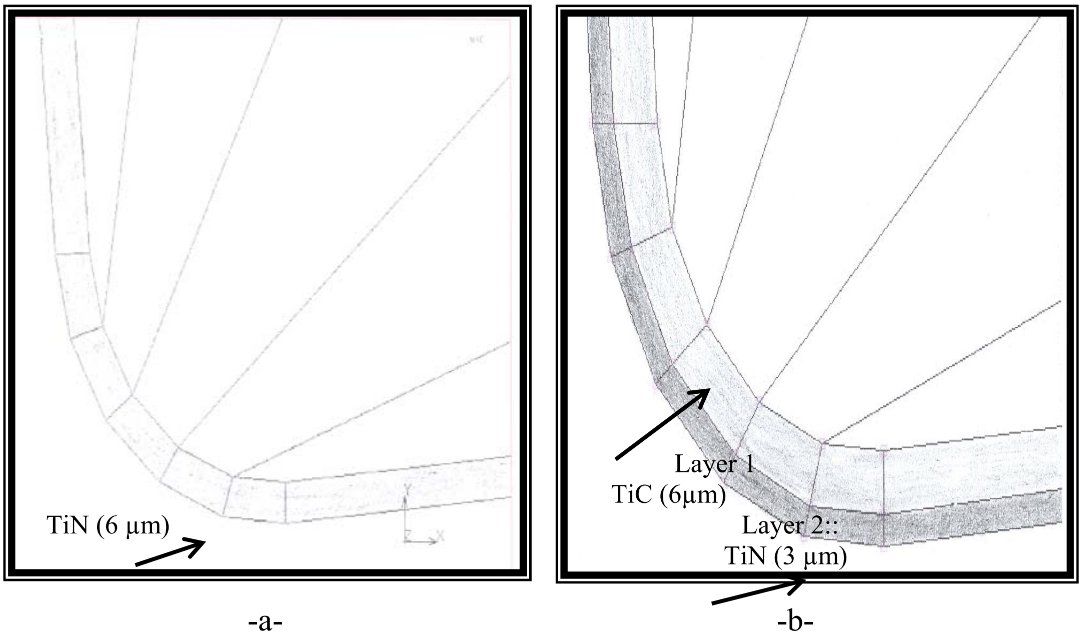
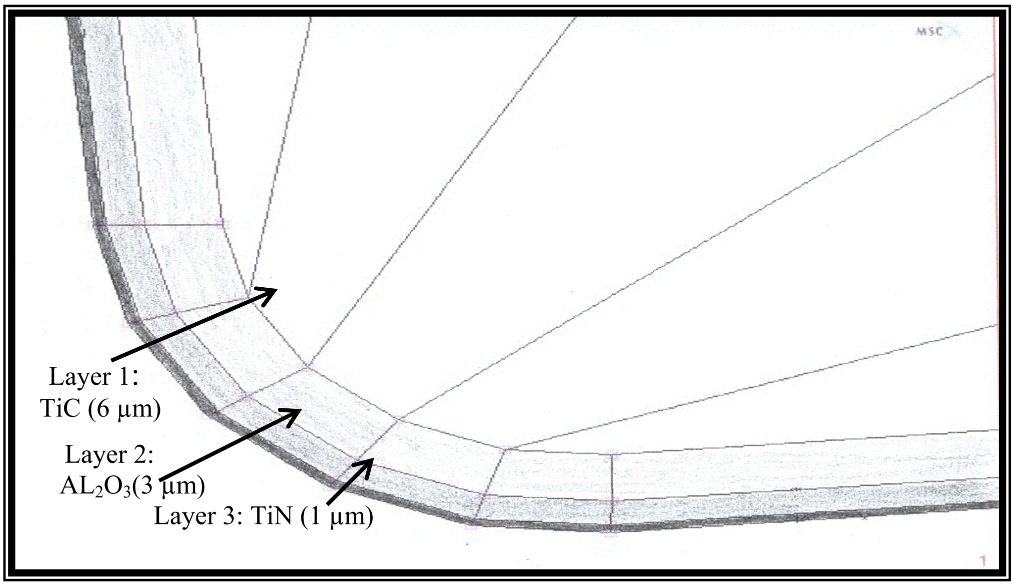


Figure (1): Representation of initial geometry and mesh for the model used in simulated tests.



-a- -b-

Figure (2): layers of coated tools being used in the simulation tests
a- (TiN), Single coating. b- (TiC/ /TiN), Double coating.



c- (TiC/AL_2O_3 /TiN), 3 layer coating.

Table(1):Constant cutting conditions for both numerical and experimental tests.

Material type	AISI 1045 St.
Cutting speed **(V_c)**	125 (m/min.)
Depth of cut **(t)**	0.5 (mm)
Feed rate **(s)**	0.08 (mm/rev.)

Table (2): Nominal composition of (AISI 1045 St) [13].

C%	Si%	Mn%	P%	S%	%Fe
0.45	0.2	0.58	0.02	0.025	remain

Table (3): Mechanical properties of work material at room temperature [13].

Ultimate tensile stress (σ_u)	515 Mpa
Yield stress (σ_y)	484 Mpa
Young's Modulus (E)	200 Gpa
Poisson´s ratio (ν)	0.29
Brinell Hardness HB	170
Shear modulus (G)	80 Gpa

Table (4): Mechanical properties of cemented carbide (WC) cutting tool [14]

Density (ρ)	14500 kg/m^3
Yield stress (σ_y)	6000 MPa
Young's Modulus (E)	650 GPa
Poisson's ratio (ν)	0.30

Table (5): Mechanical properties of coating layers [15].

Coating layer	TiC	AL_2O_3	TiN
Young's Modulus(E)[Gpa]	450-496	340-400	250
Poisson's ratio(ν)	0.19-0.24	0.23	0.25
Density(ρ)[kg/m^3]	4650-49000	3780	4650

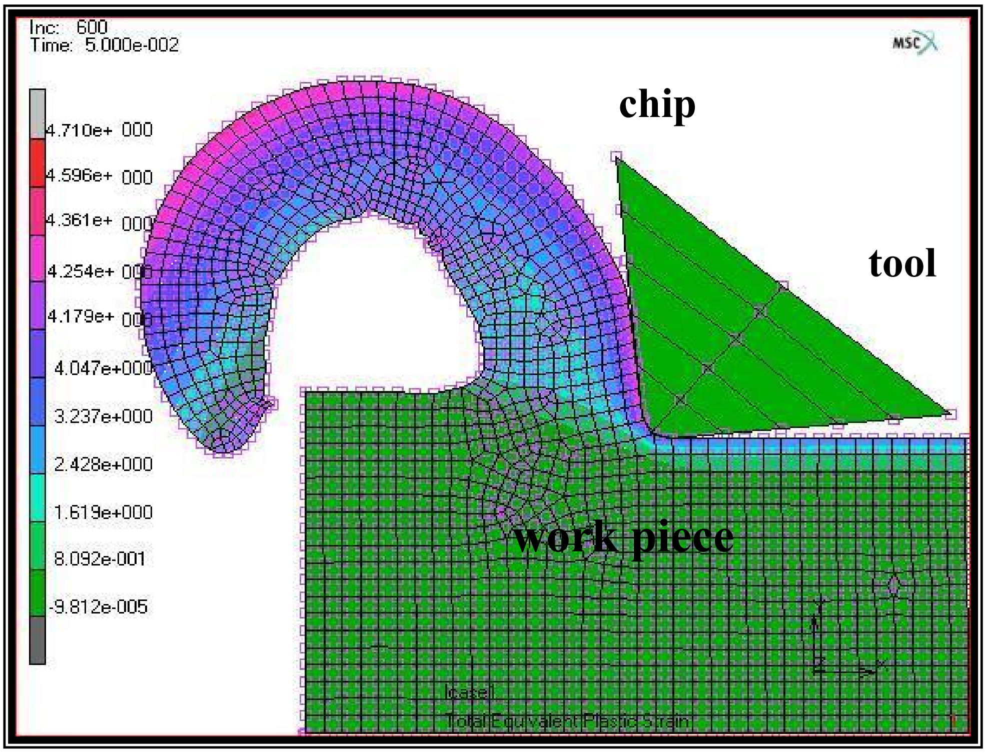


Fig (3):A representative successful simulation test for chip formation process through the MARC code.

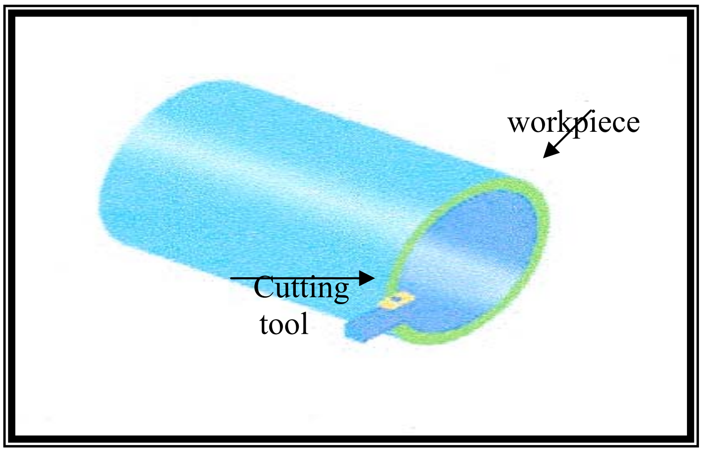


Figure (4): Orthogonal cutting, end tube turning.

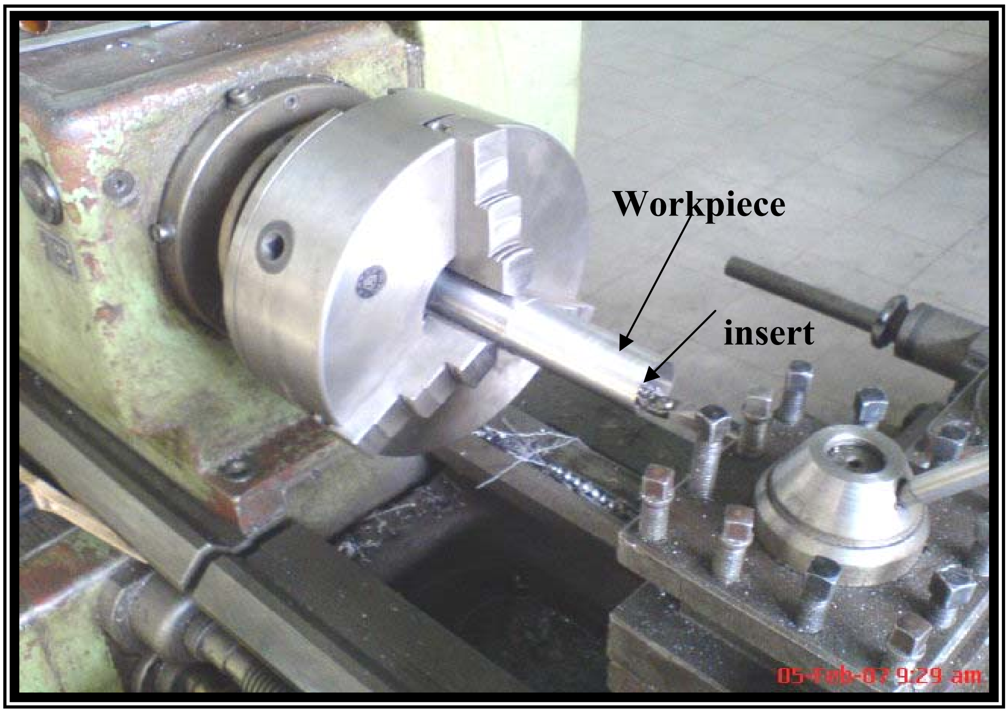


Figure (5): Photograph of the turning machine, showing the workpiece and insert used.

Table(6): Specifications of centre lathe machine used in experimental tests.

Spindle speed	Feed rate	Center length	Total power
22.4 - 2000 r.p.m	0.08 - 6.4 mm/rev.	1500 mm	6.6 KW for 50 Hz

Table(7): Tool geometry for the coated cutting tools

Tool rake angle	-5º
Tool clearance angle	5º
Measured cutting edge radius	40μm

Uncoated tool   coated 1 layer   coated 2 layers   coated 3 layers

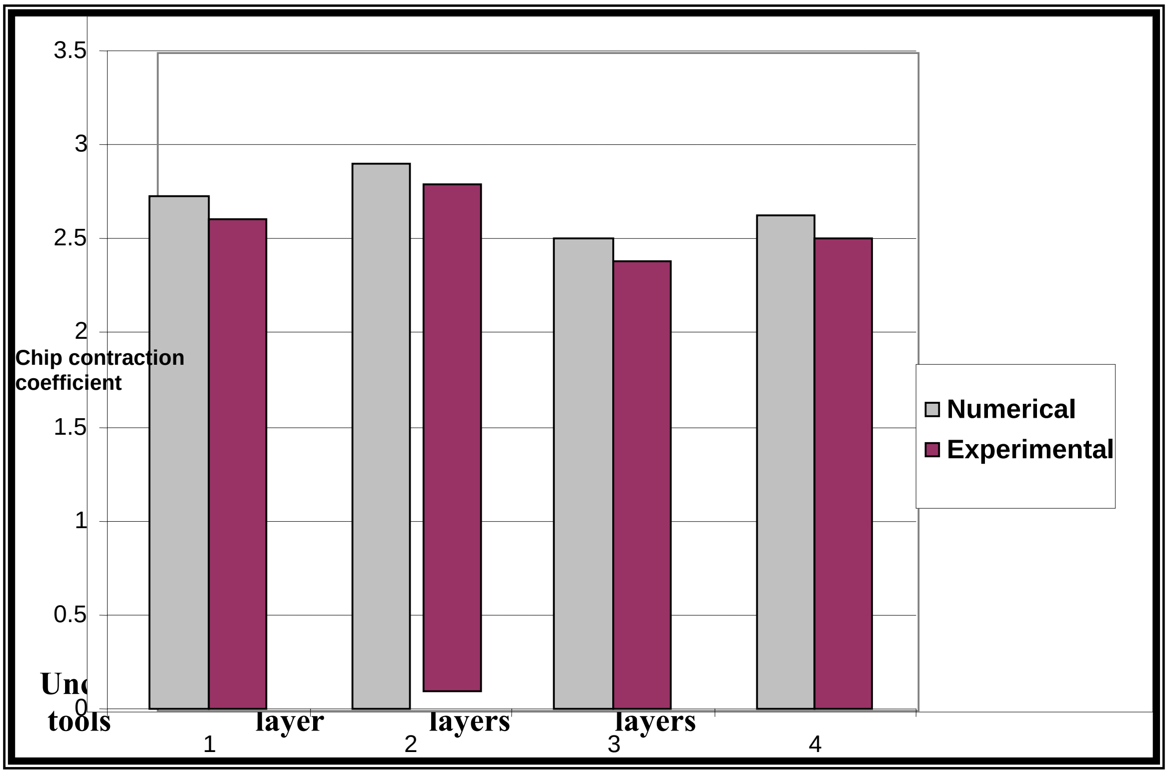


Figure (6): Comparison between FEM and experimental results for chip contraction coefficient.Where:

Insert no. 1 is uncoated.

Insert no. 2 isTiN coated.

Insert no. 3 is TiN/TiC coated.

Insert no.4 is TiN/Al_2O_3/TiCcoated.

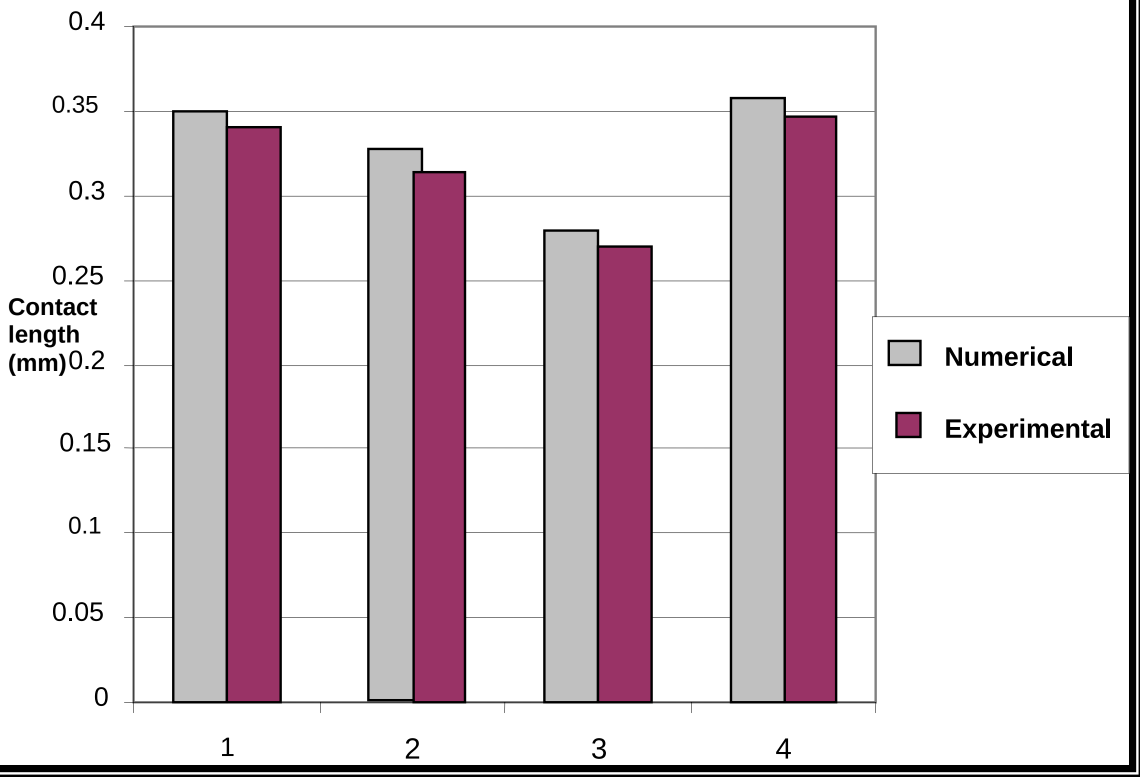
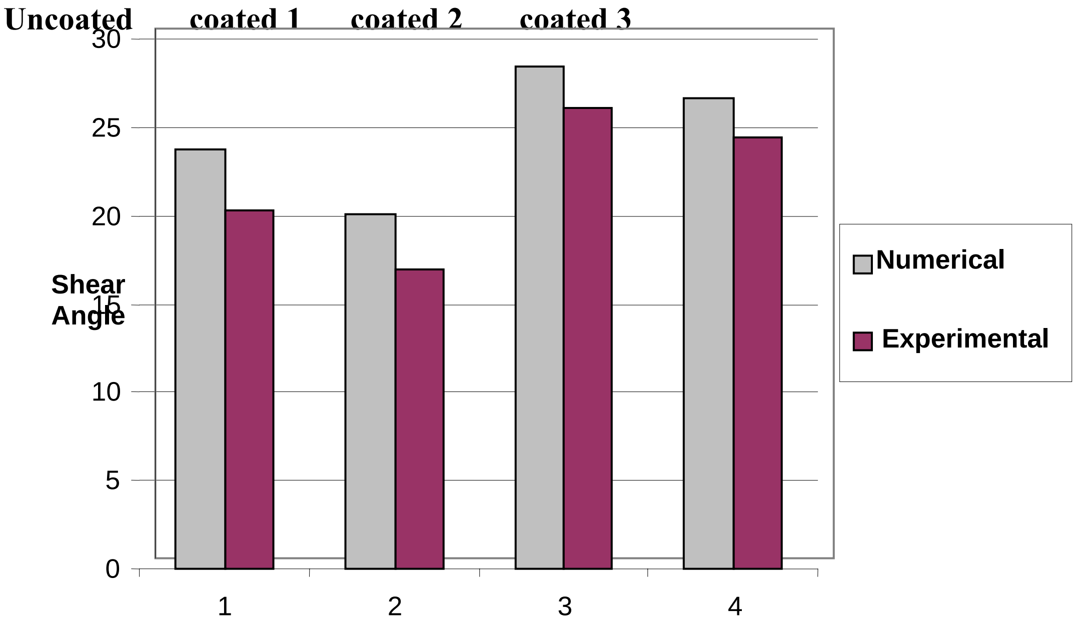


Figure (7): Comparison between the FEM and exp. results for contact length contact length.



Figure(8):Comparison between the FEM and exp.results for the shear angle.