A Finite Element Analysis of Orthogonal Machining Using Different Tool Edge Geometries

Dr. Maan Aabid Tawfiq*   Suha Kareem Shahab**

Received on:5/9/2005
Accepted on: 26/11/2006

Abstract

This paper summarizes the effects of edge preparation of the cutting tool in orthogonal cutting on the following variables: stress distributions at the tool rake face, cutting forces and tool-chip contact length. The Finite Element Method (FEM) is selected using the ANSYS /V4.5 code. Six models of cutting tools have been suggested having edge radii of (0.01, 0.05, 0.1, 0.15, 0.2, and 0.25) mm. The results obtained provide a fundamental understanding of the process mechanics for cutting with realistic cutting tool edge radius in order to assist in the optimization of tool edge design. The results show that the optimum edge radius from the six simulated models is (0.05) mm; this edge radius gives minimum value of effective stress. The results show also that the optimum edge radius that shows minimum tangential cutting and feed forces is (0.01) mm. The results investigated that the tool-chip contact length is increased, until reaching maximum value of (2.4) mm at (r=0.15mm), and minimum value of (0.75) mm at (r=0.01mm). The maximum relative difference between simulated results of this work and other previous paper results is (2% - 17%) for the tool effective stresses, (5%) for the tangential force, and (11%) for the feed force.

Key words: FEM, edge radius, orthogonal machining

التحليل بطريقة العناصر المحددة للقطع المتعامد عند قيم مختلفة من هندسية حافة عدة القطع

الخلاصة

تم في هذا البحث التركيز على دراسة تأثير التغير في هندسية العدة وبالتحديد نصف قطر شكل (cutting edge radius) على مجموعة من العوامل المتضمنة توزيع القاطع تقــوس حافــة الحد الاجهادات على وجه العدة, كذلك توزيع قوى القطع وطول منطقة التماس بين وجه العدة والنحاته (chip). وقد تم اختيار قيم منتخبة من نصف اقطار التقوس وهي: ,0.05 , 0.01, 0.1, 0.15) 0.20, 0.25)ملم، حيث أمكن محاكاة هذه الحالات باستخدام برنامج (ANSYS/V4.5) والذي أمكن تحويرة بما يخدم أهداف البحث. تم الحصول على نتائج أعطت فهما واضحا لتأثير هذا العامل على بقية المتغيرات حيث أظهرت النتائج بأن أفضل قيمة لنصف قطر تقوس الحافة هو (0.05)ملم والتي تظهر عليها أصغر القيم من الاجهادات الفعالة، بينما أظهرت النتائج بأن أصغر القيم لقوتي القطع المماسية والتغذية تكون عندما تصبح قيمة نصف قطر تقوس هندسية الحافة (0.01)ملم ، كما واكدت النتائج بان طول منطقة التماس بين وجه العده والنحاته يزداد الى ان تصل قيمته القصوى (2.4)ملم، وذلك عند نصف قطر تقوس مقداره (0.15) ملم، بينما يكون طول هذه المنطقة أقل مايمكن وهو(0.75) ملم وذلك عند نصف قطر تقوس مقداره

http s://doi.org/10.30684/etj.25.4.5
2412-0758/University of Technology-Iraq, Baghdad, Iraq

(0.15) ملم، كذلك أمكن تحديد الاختيار الأمثل لتصميم حافة العدة ومقارنة النتائج المستحصلة مع بحوث منشوره وأظهرت النتائج توافقاً واضحاً مع نتائج لباحثين آخرين في هذا المجال حيث وجد بأن الفارق بين القيم التقديرية العددية والقيم في البحوث السابقة يتراوح بين (٢%-١٧%) للاجهادات الفعالة للعدة و (٥%) لقوة القطع المماسية و (١١%) لقوة التغذية.

1-Introduction:

In metal cutting, the modification of the tool edge geometry is referred to as edge preparation, the purpose of edge radius preparation is to strengthen the cutting edge and prepare a surface for deposition of coatings. In addition, hone edges can reduce the initiation of notch wear, and are usually employed in finish cut [1]. The objective effect of the cutting tool geometry is to establish a predictive theory that would enable to predict cutting performance. The models are mainly established to obtain a better understanding of the cutting mechanism itself due to the tremendous difficulties, which occur in attempting to measure temperatures, strain rates, stresses and other variable factors. The (FEM) can be applied to model and simulate the machining process. Furthermore, modeling of metal cutting processes can reveal useful information, which may not be measured directly during the cutting process itself. With a model, the interaction of the tool and the chip can be examined, if a valid model exists, the model can be used to vary certain material or process parameters. On one hand, this may help to design materials or tools which are more suitable for the machining operations, and also on the other hand, this procedure can be used to find new optimized tool geometries. Most of the early research work on the FEM modeling of orthogonal cutting was limited by the assumption of a perfectly sharp cutting edge which requires a predefined criterion for chip separation from the workpiece along the predefined parting line [1]. In recent years, there have been increasing attempts to extend the FEM modeling technique to the cutting with non-sharp tools. *Strankowski and Carroll* (1985)[2] presented an FEM of orthogonal metal cutting, the model employed an updated Lagrange formulation for plane strain conditions They used two-dimensional Finite Element software code (Nike2D). The model was able to predict chip geometry, residual stresses in the workpiece and tool. *Arsecculartne et al.* (1998)[3] described a method for predicting cutting conditions in which the cutting edge starts to deform plastically when oblique machining for a range (0.2-1.4) mm of edge radius tools, they showed how tool stresses and temperatures are determined from machining theory that can be used together with experimental high temperature data. A comparative study was made between predicted and experimental results for plain carbon steel and a range of cutting conditions, they showed good results. *Chung-Shinchang* (1998)[4] presented a new model for edge radius (0.35) mm with chamfered main cutting edge. He observed that the values of three dimensional cutting forces are larger by about (20%) in case of tool wear as compared to those without tool wear and the cutting forces increase greatly when tool wear occurs. The results obtained from the proposed model showed good agreement with the experimental data on cutting forces. *Kim et al***.** (1999) [5] studied the effect of the edge radius for a cemented carbide tool on the cutting forces and temperature, using a FE orthogonal cutting model, and compared the results with the experiments. Their simulation results showed that increased tool edge radius alters the temperature distribution of the tool and shifts the position of maximum temperature closer to the tool tip. Experimental results also indicated that cutting forces increase as the tool edge radius increases within the same limit in the simulated models. *Shatla et al.* (2000) [6] applied the Lagrangian formulation using FEM simulation to study the influence of edge preparation (hone/chamfer) on tool temperature and stress in orthogonal cutting of (H13) tool steel (46 HRC). Simulation results showed that the effective or normal stress of the tool reached a minimum value when using a moderate edge radius (0.1) mm. The tool with an excessive edge radius resulted in a significant increase in the tool stress and shifted the stress concentration close to the flank face. In the same study, the effects of different chamfer geometries on the tool rake and flank temperatures were also summarized. *Leopold* (2000) [7] used new method Visioplasticity–FEA. This method reduces the gap between theory and practice. Suggestions for overcoming some practical difficulties and extending the scope of this visioplasticity based predictive modeling approach are also considered. He found relationships between edge radius with grooved tool radius, cutting forces, the coefficient of the chip contraction, and tool-chip contact length. *Altan et al.* (2002)[8] performed FEM simulation to investigate the effect of tool edge geometries honeded of (0.01, 0.05, 0.1) mm, and chamfered of(0.1mm×15˚,0.1mm×25˚,0.2mm×15˚, 0.2mm×25˚) upon chip formation, cutting forces and process variables (temperature, stress, and strain) in orthogonal cutting and compared the results with the available experimental data. The results showed that both force components increase with increasing edge radius. Also the degree of plastic deformation in the secondary shear zone on the machined surface increases considerably as the edge radius increases. It is also showed that the edge radius does not have a significant influence on the magnitude of both stress components. *Ozel* (2003)[9] studied the influence of edge preparation in (CBN) cutting tool on process parameters and tool performance using FEM simulations and experimental tests. A set of orthogonal cutting experiments using honed (0.02) mm and chamfered (0.1mm×25˚) tools were performed. The results showed that the zone of workpiece material is formed under the chamfer acting as an effective rake angle during cutting. *Altan* (2003)[10] performed FEM simulation to investigate the effect of tool edge geometries honed of (0.01, 0.05, 0.1, 0.2) mm, chamfered of (0.1mm×15˚, 0.1mm×25˚,0.2mm×15˚, 0.2mm×25˚), and sharp edge upon cutting force, chip flow, temperature, and tool stress in orthogonal cutting. *Altan and Yen* (2004) [11] studied the influence of the cutting edge radius (9, 14, 18, 20 and 24) µm of coated tools on chip formation in orthogonal cutting of

Alloy steel. The results showed that the optimum edge radius has been revealed so as to minimizing the effective stress in the cutting tool to be (r =14µm).

2-Finite Element modeling

The FEM provides a systematic procedure for the derivation of the approximation functions over sub-regions of the domain. In FEM desecrates a structure into several elements (pieces of the structure). Then reconnects elements at nodes as if nodes were pins or drops of glue that hold elements together. This process results in set simultaneous algebraic equations. For a general linear and/or nonlinear static problem the equations for a Finite Element analysis are expressed as:

$\{F\}=[K]\{U\}$

where: F is the vector matrix for the forces on the element,

K is the stiffness matrix, and

U is the vector of nodal displacements to be determined

The model shown in Fig.(1) is built as a general orthogonal cutting model. The length of the workpiece is assumed to be 30mm. The uncut chip thickness (or depth of cut) is (0.5) mm while the height of workpiece is assumed to be (10) mm. The cutting tool was modeled with rake angle (γ) equal to (10˚) and the clearance angle (α) is assumed to be (5˚). Six models of cutting tools have been suggested having edge radius of (0.01, 0.05, 0.1, 0.15, 0.2, and 0.25)mm. The minimum one (edge radius of 0.01 mm) is supposed to be sharp. Modeling geometry and dimensions is done using the Cartesian coordinate, 2-D model. Both the workpiece and the tool are modeled with nonlinear quadrilateral elements. The tool was modeled with a fine mesh near the cutting tool tip and the other portion far from the tip was modeled coarsely. The model was divided into three parts with Lagrangian solid elements chosen to be (plane42) (four-nodes) this solid element is used for cutting tool modeling, while Lagrangian solid element is chosen (visco106) (four-nodes), this element is used for chip and workpiece modeling. The solid elements (contac48), is chosen between tool and workpiece and between tool and the chip. The initial geometry and mesh are presented in Fig. (1), which consists of the following nodes and elements.

- 333 nodes (128 nodes for modeling of plane 42 and 205 nodes for modeling of visco106)
- 283 element (173 visco elements and 110 plane elements).

The mesh density for the chip was meshed more carefully specially on the line of contact between the chip and workpiece, where most be correspondent in mesh density in order to allowing chip separation take place, while the remain lines of the workpiece was defined to be free because the workpiece is out of our concern for this analysis.The boundary conditions are also shown in Fig. (1), the workpiece is fixed in all directions, and the tool is allowed to move towards the workpiece. The tool is considered to be rigid and moving at a constant cutting speed (V_c) in negative x direction. For this model, the cutting speed is assumed to be constant (150) m/min. Constraints were placed on the tool allowing movement only in the x direction. The cutting conditions are reported in table (1), the coefficients of friction between chip and tool and between chip and workpiece was assumed to be constant (μ=0.5).

3-Modifying the ANSYS code for Metal Cutting Process

Joining between nodes is extremely useful in modeling and can be used successfully to simulate the metal cutting process. To simulate the chip separation, the workpiece is tied with chip segment by constant force in negative y direction. This force makes the chip and workpiece seem to be as one part till the chip formation process takes place. In this model it is required to select multiple pairs of nodes to be joined during the analysis and are therefore defined, when the failure criteria is adopted, the node pair is removed from the join, and the node motion is computed for the separation of nodes. The join ceases to exit, when all pairs of the join have failed, after which all the nodes of the join are treated as separate nodes. A tying force was included between the part of the workpiece that, is removed during the cutting (chip), and the remaining material (workpiece). When the joining force reaches certain critical value (chip separation criterion is reached), debond of the node pair in this region takes place and the two nodes move in different directions, which depends mainly on the assumed edge radius. The ANSYS code in this study is selected using Lagrange technique, which needs an overall view on material properties to get accurate results. The path for separating the chip from the workpiece is predetermined, as shown in Fig.(2), showing the initial contact and the start of separation and the steady state condition.

4-Material Modeling:

The material used for the workpiece is (AISI 1006 Steel), its mechanical and thermal properties are shown in table (2). The initial temperature is assumed to be (25ºC). A *Von-Mises* yield criterion is assumed, and isotropic strain hardening rule is applied. The tool is assumed to be (cemented carbide WC), whose mechanical properties are given in Table (3), the tool material has a hardness of (1700HV).

5-Results and Discussion:

5-1 Effect of Edge Radius on the Cutting Tool Stresses:

The shear stress distributions for the various edge radii, under identical machining conditions, are shown in Fig. (3). The shear stress was found to be maximum near the cutting edge due to high pressure caused by plastic deformation of the chip layers near the cutting edge in addition to the effect of sticking friction that affects the behaviors of contacting area resulting in high values of shear stresses at this region. It is clear also from Fig.(3) that the maximum value for the shear stress when using tool with edge radius within the range of (0.01-0.15) mm is increased within the limit of (237-550) MPa. But when using tool edge radius within (0.2- 0.25) mm, the maximum shear stress is decreased from (373 to 295)MPa. This may be due to the increasing area of contact, which is more effective than the contact length.

The effective stress distributions for the six edge radii are shown in Fig. (4), the maximum effective stress occurs at the tool tip, due to the existence of the sticking zone. Sliding takes place beyond the sticking region and therefore, one can observe that the effective stress decreases to zero at the point where chip leaves the tool face. Fig.(4) shows that when using tool with edge radius within the range of (0.05– 0.2) mm, the maximum effective stress is increased within the limit of (619 – 3690) MPa and then decreased when using edge radius of (0.25) mm in order to reach the value of (3140) MPa, while when using tool with edge radius of (0.01) mm the effective stress is (3250) MPa.. More details for stress distribution contours at the various tool edge values for the simulated tests are shown in the Appendix (A&B).These results show that the edge radius has a complex influence on the magnitude of both stress components (shear stress and effective stress). It is clear from the simulated results for the six edge radii, which are shown in Fig. (5), the optimum edge radius is (0.05) mm, where it minimized the effective stress to reach the value of (619) MPa. It can be seen from Figs.(4, 5) that the shear stress is constant over a wide region near the cutting edge, where the effective stress was very high, indicating that Coulomb's law of sliding friction may not be appropriate here. The conclusion was also reached by *Zorev* [12] and other published papers in references [8, 13, 14-16]. The papers showed that the stresses singularity at the point of chip separation from the rake face has never been explained and it is quite possible that actual stresses and stress distributions may have not yet come to light due to a significant scatter in the results obtained. These results show that the edge radius has a complex influence on the magnitude of both stress components (shear stress and effective stress), whereas the lengths of the sticking and sliding regions for all tools are slightly different. These results agree with the experimental and numerical results by *Altan et.al. and Astakhov* in the published papers [8,14] respectively.

5-2 Effect of Edge Radius on Cutting Forces:

Fig.(6) shows that both forces increase as the edge radius increases from (0.01 to 0.25) mm. A comparison was made between predicted, experimental and simulated results from previous paper, showed good results. Apparently, this increase in forces is due to the increase of the cutting edge radius. In addition, the increase in chip thickness leads to a larger shear plane angle in the deformation zone, which increases the cutting forces. The predicted values of (F_c and F_t) are in good agreement with experimental and numerical measured values from previous published papers. A comparison was made between predicted, experimental and simulated results from previous paper [10], showed good results. Apparently, this increase in forces is due to the increase of the cutting edge radius, which requires larger forces for material shearing. The predicted values of (F_c and F_t) are in good agreement with experimental and numerical measured values from previous published papers. The maximum difference between cutting forces from this work and cutting forces from previous published paper [17] is less than (5%) for the tangential force and (11%) for the thrust force, this may be due to uncertainties in the material properties or due to some difference in the cutting conditions.

5-3 Effect of Edge Radius on Tool-Chip Contact Length:

It is clear from Fig.(7), that the contact length (L_c) increases as the edge radius increases within a range of (0.01– 0.15) mm. The large normal contact pressure near the edge of the tool causes sticking and sliding friction between the chip and the rake face of the tool. Therefore, the material near the edge radius continues to deform and the temperature can be very high locally in some areas of the chip, resulting in further thermal softening. This thermal softening reduces the materials strain – hardening capacity, so the instability takes place in a narrow band and finally forms an intense shear band [14].

6-Conclusions:

The main conclusions, which can be deduced from the present work, can be summarized as follows:

1. The results show that the optimum edge radius from the six models simulated is (0.05) mm; this edge radius gives minimum value of effective stress.
2. The optimum edge radius for minimum tangential cutting and feed forces is (0.01) mm.
3. The results show that the tool-chip contact length is increased, until reaching maximum value of (2.4) mm at (r = 0.15mm), and minimum value of (0.75) mm at (r = 0.01mm).
4. The maximum relative difference between simulated results of this work and previous paper results is (5%) for the tangential forces, (11%) for the thrust force, and (2% - 7%) for the tool effective stresses.

References

1- Ozel, T., and Zeren, E., “Hard turning technology”, Rutgers University, Piscataway, New Jersey, USA, 2003.

2- Strenkowski, J.S., and Carrol III, J.T., “A finite element model of orthogonal metal cutting”, Trans. Journal of Engineering for Industry, Vol.107 No.4, pp.349-354, 1985.

3- Arsecularatne, J.A., Fowle, R.F., and Mathew, P.,“Prediction of chip flow direction, cutting forces and surface roughness in finish turning”, Journal of Manufacturing Science and Engineering, Vol.120, No.1, pp.1-12, 1998.

4- Chung, C.S., “A force model for nose radius worn tools with a chamfered main cutting edge”, International Journal of Machine Tools & Manufacture, Vol.38, pp.1467-1498, 1998.

5- Kim, K.W., Lee, W.Y., and Sin, H.C., “A Finite-element analysis of machining with the tool edge considered”, Journal of Materials Processing Technology, Vol.86, pp.45-55, 1999.

6- Shatla, M., Yen, Y.-C., and Altan, T., “Tool-workpiece interface in orthogonal cutting–application of FEM modeling”, Transactions of NAMRI/SME, Vol.XXVIII, pp.173-178, 2000.

7- Leopold, J., “The application of Visioplasticity in predictive modeling the chip flow, tool loading and surface integrity in turning operations”, Proceedings of the CIRP International

Workshop on Modeling of Machining Operations, University of New South Wales, Australia, August 2000**.**

8- Altan, T., Yen, Y.Ch, and Anurag, J., "A finite element analysis of orthogonal machining using different tool edge geometries", (ERC/NSM), The Ohio State University, USA, 2002.

9- Ozel, T., "Modeling of hard part machining: effect of insert edge preparation in CBN cutting tools", Journal of Materials Processing Technology, Vol.141, pp.284-293, 2003.

10- Altan, T., "Modeling of metal cutting using FEM", (ERC/NSM), The Ohio State University, January 2003.

11- Altan, T., and Yen, Y.C., "Influence of cutting edge radius of coated tool on chip formation in orthogonal cutting of alloy steel", (ERC/NSM), The Ohio State University, 2004**.**

12- Zorev, N.N., "Metal cutting mechanics", Pergamon Press, Oxford, UK, 1966.

13- Bayoumi, A.E., Xie, J.Q., and Zbib, H.M., "FEA modeling and simulation of shear localized chip formation in metal cutting", International Journal of Machine Tools & Manufacture, Vol.38, pp.1067-1087, 1998.

14- Astakhov, V.P., and Outeiro, J.C., "modeling of the contact stress distribution at the tool-chip interface", Proceedings of the CIRP International Workshop on Modeling of Machining Operations, ENSAM, Cluny, France, May 2004.

15- Altan, T., "Sensitvity analysis of flow stress and friction in finite element simulation of orthogonal cutting", (ERC/NSM), The Ohio State University, 2004.

16- Ozel, T., "Influence of friction models on finite element simulations of machining", The State University of New Jersey, USA, 2004**.**

17- Endress, J.W, Manjunathaiah, J.,and Schimmel, J.,**"**Edge radius variability and force measurement considerations**",** Transactions of the ASME, Vol.122, pp.590-593, 2000**.**

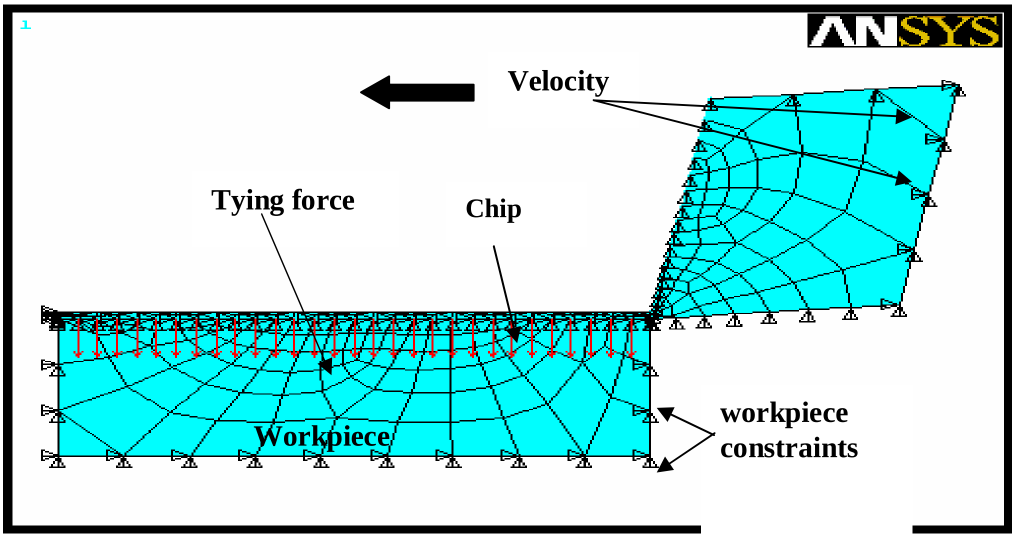


Fig. (1): Representative model boundary conditions (showing the workpiece constraints, tying force between chip and workpiece, velocity direction of the cutting tool).

Table (1): Cutting parameters selected for numerical tests.

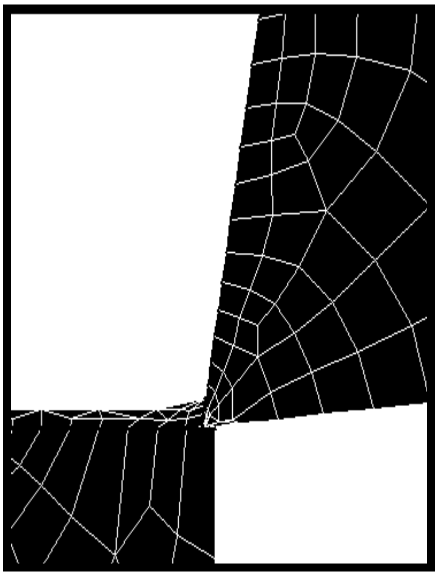
Material	AISI 1006 st.
Cutting speed (V_c)	150 m/min.
Depth of cut (t_1)	0.5 mm.

Table (2): Mechanical and thermal properties of (AISI 1006 Steel) .

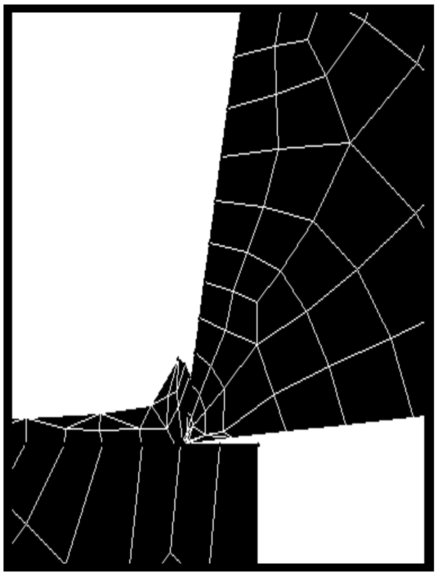
Density	(ρ)	7850 kg/m^3
Young's Modulus	(E)	220 GPa
Poisson's ratio	(ν)	0.30
Shear Modulus	(G)	82 GPa
Yield stress	(σ_y)	350 MPa
Room temperature	(T_o)	25 ºC

Table (3): Mechanical properties of Cemented Carbide(WC) cutting tool.

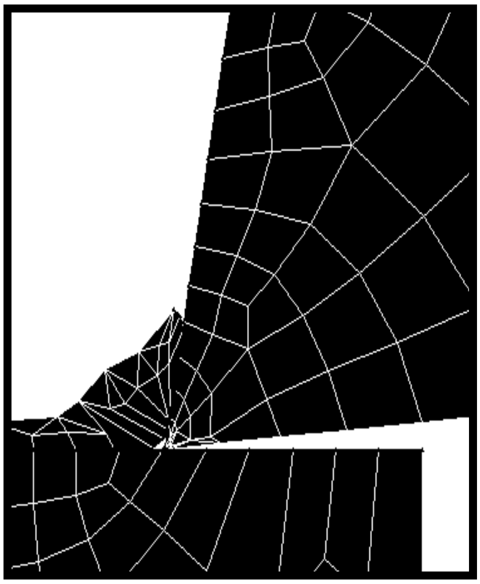
Density	(ρ)	14500 kg/m^3
Yield stress	(σ_y)	6000 MPa
Young's Modulus	(E)	650 GPa
Poisson's ratio	(ν)	0.30



- a -



-b-



-c-

Fig. (2): The stages of the simulation tool advance through the workpiece in steady state condition with different cutting distances:

a- At initial contact , b- At cutting distance of (2) mm, c- At cutting distance of (6) mm**.**

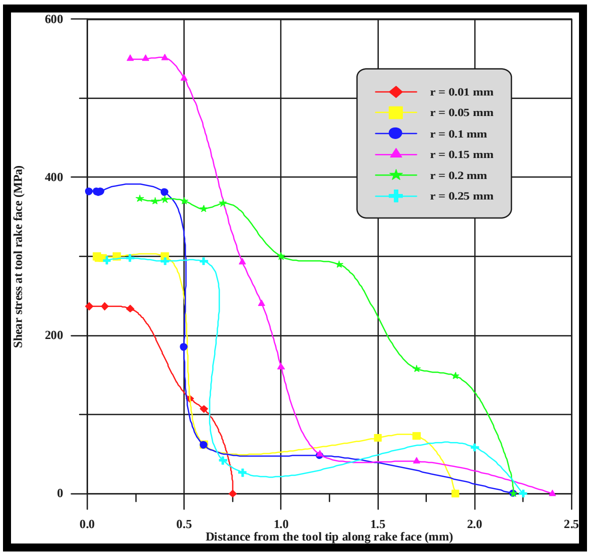


Fig. (3): Predicted shear stress (τ_f) distributions on the rake face of the honed tool with different edge radii.

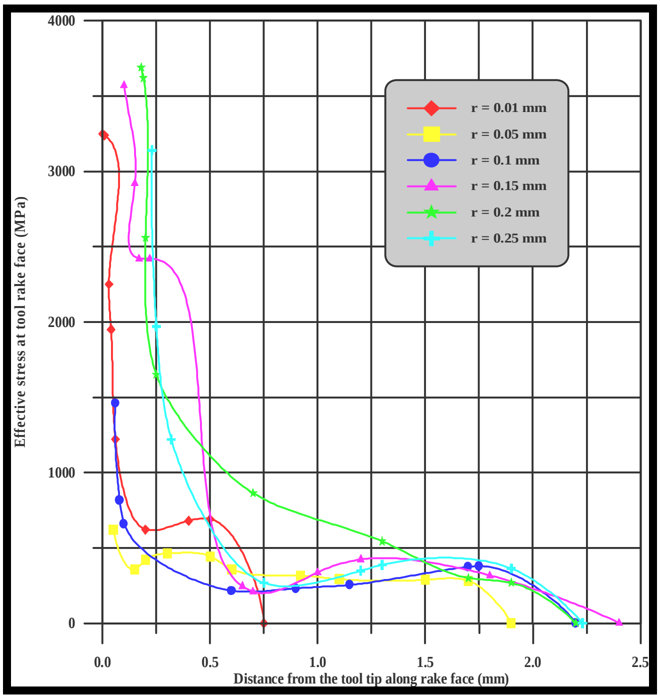


Fig. (4): Predicted effective stress (σ_n) distributions on the rake face of the honed tool with different edge radii.

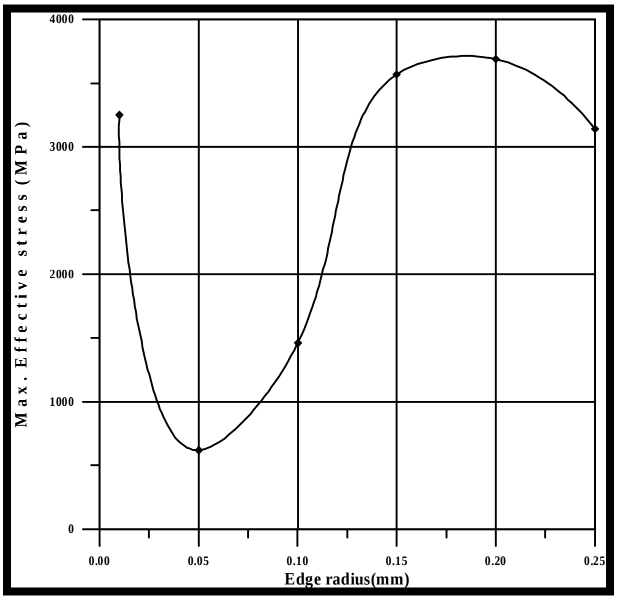
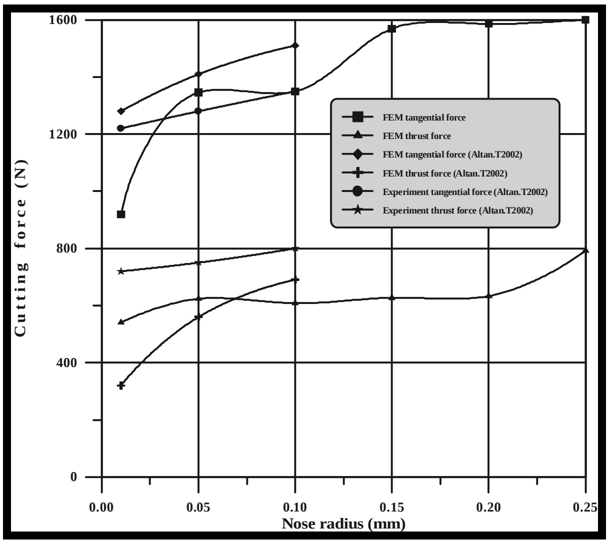


Fig. (5): Relation between edge radius and maximum effective stress.



Edge radius (mm)

Fig.(6):Comparison of predicted tangential force and thrust force with experimental data Ref.[8].

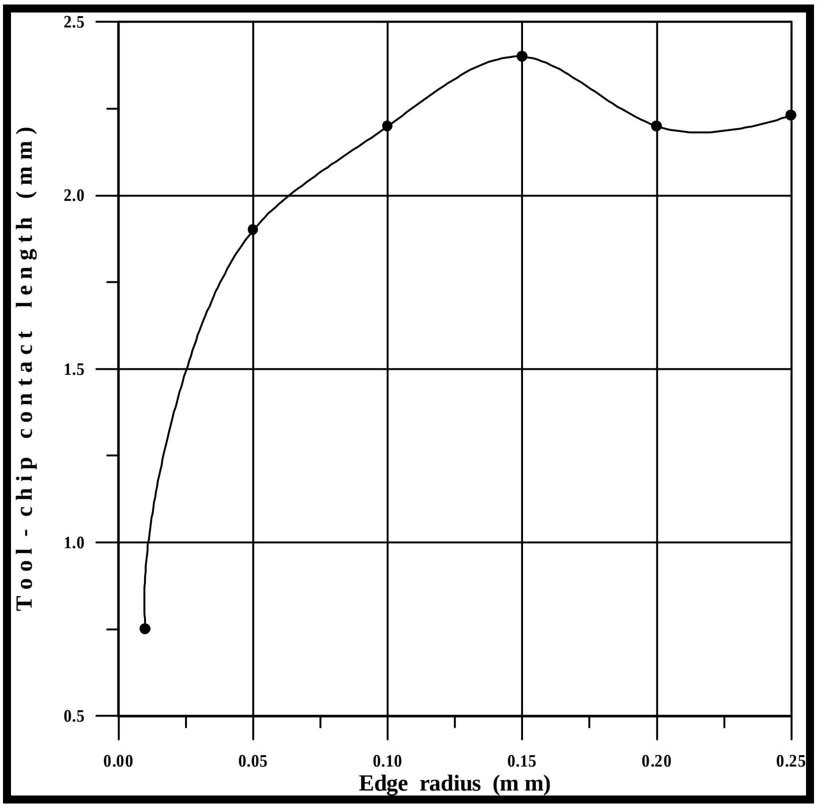
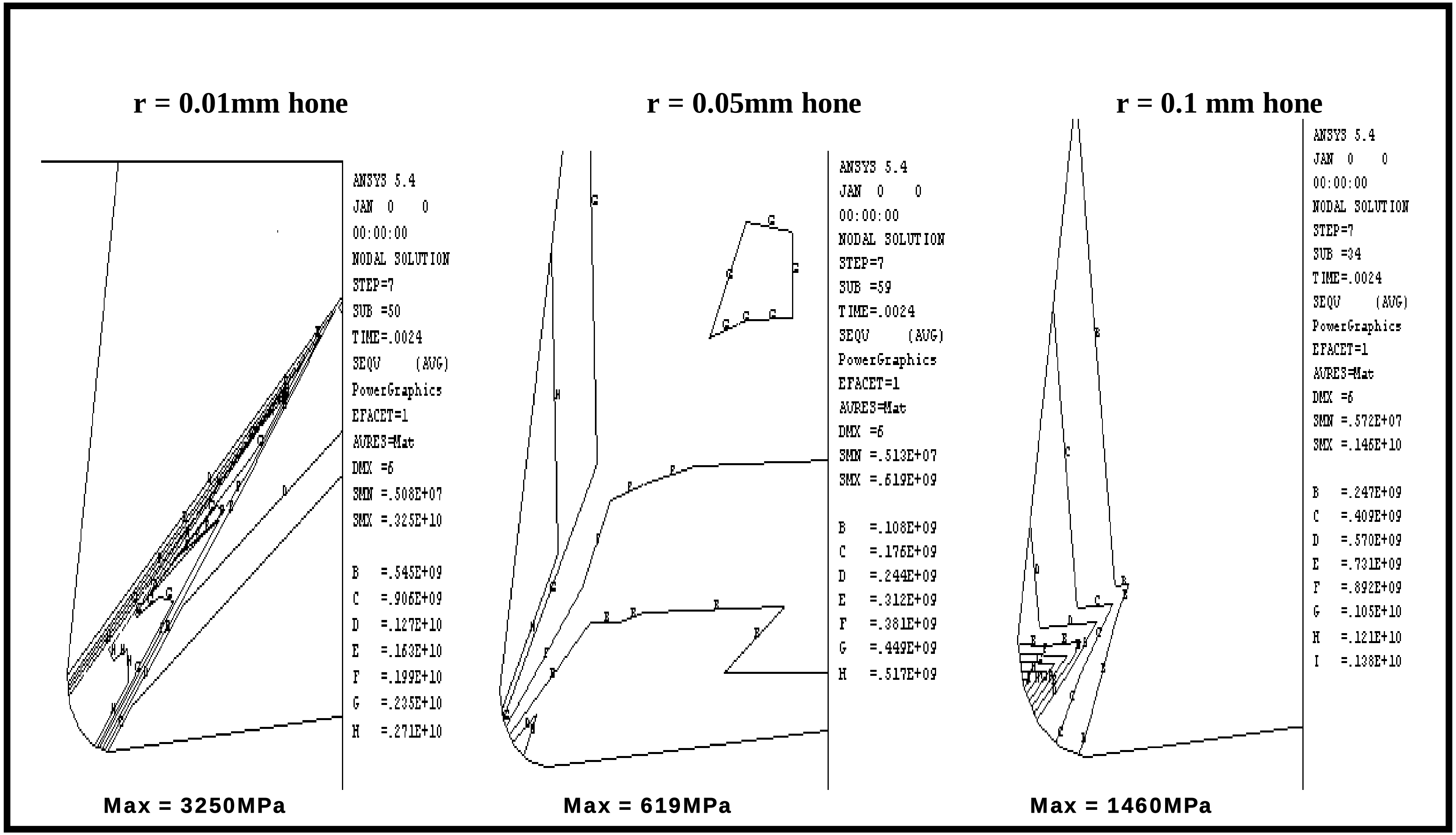
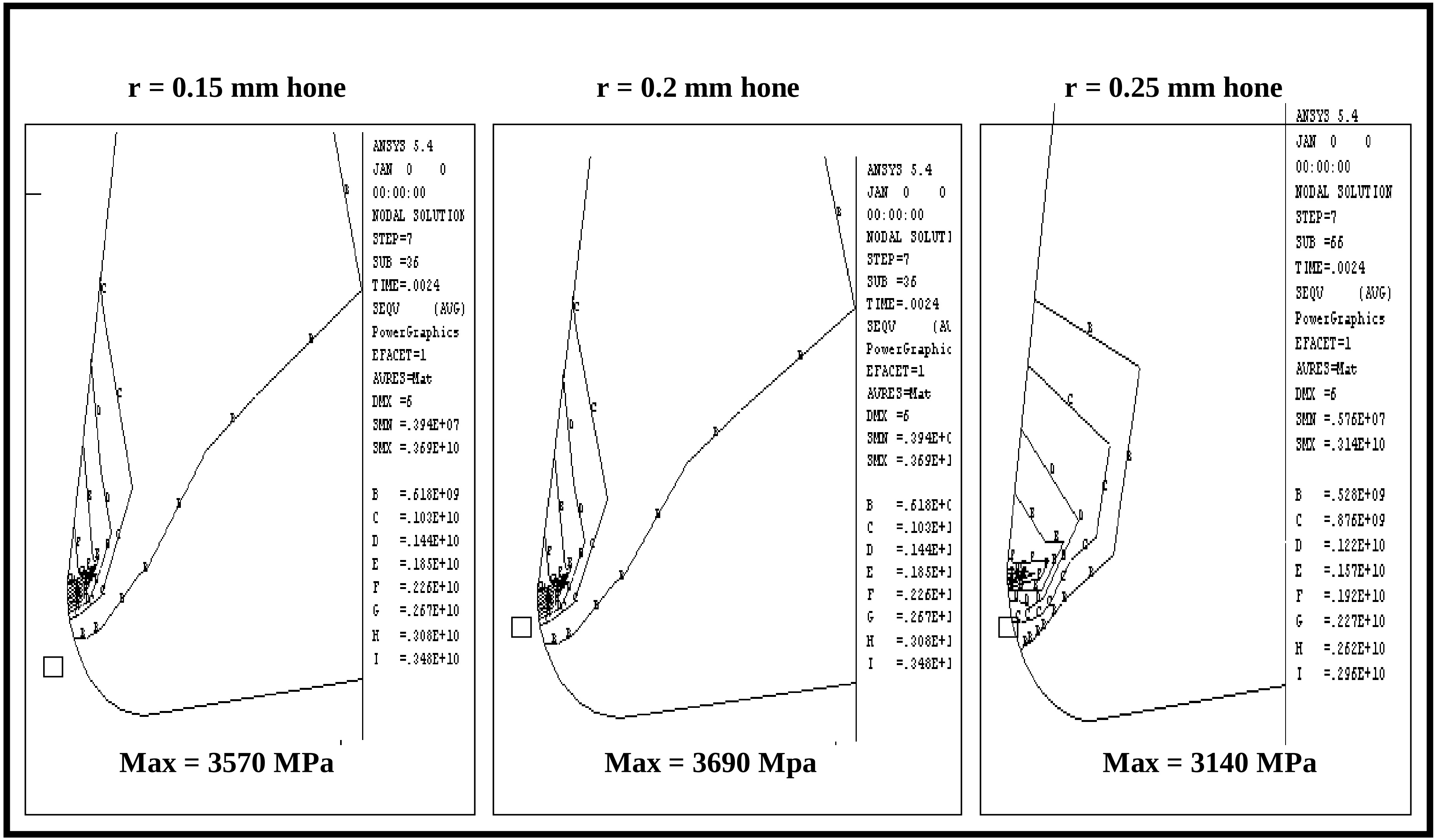


Fig. (7): Effect of edge radius on contact length at tool - chip interface for the simulated tests.



Appendix (A): The effect of edge radius on tool effective stresses (AISI 1006 steel) for the simulated tests.



Appendix (B): The effect of edge radius on tool effective stresses (AISI 1006 steel) for the simulated tests.