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Finite Element Analysis to Study the Effects of the Workpiece Flow Stress Models on Cutting Variables in Orthogonal Cutting

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ABSTRACT

Turning process is a common machining process to produce cylindrical shape parts. Understanding of material removal concepts in metal cutting is very important in design process and cutting tool selection to ensure the quality of the products.

For this purpose, orthogonal cutting simulations of AISI 1045 steel are performed and the model used in simulations is validated. Effects of work piece flow stress models on cutting variables such as cutting forces, chip geometry and temperature are investigated by comparing simulation results with experimental results available in the literature. Results show that flow stress models have a major effect on calculated results .The results of the simulations show that Oxley material model is able to give more accurate results for used cutting conditions in the analysis, however errors in calculating shear angle and thrust force are higher than Johnson-cook and Zerilli-Armstrong material models.

Keywords: Finite element simulation, Flow stress model, cutting force, temperature

دراسة تأثير نموذج إجهاد انسياب المشغولة على متغيرات القطع في قطع متعامد باستخدام طريقة العناصر المحددة

الخلاصة

عملية الخراطة هي العملية التشغيل الشائعة لانتاج الاشكال الاسطوانية .فهم عملية ازالة المعدن جدا مهمة في عملية التصميم وختيار عدة القطع المناسبة لسيطرة على نوعية الانتاج .

في هذا البحث تم محاكات عملية قطع متعامد لمعدن AISI 1045 بستخدام العناصر المحددة لدراسة تاثير اجهاد انسياب المشغولة على متغيرات القطع مثل قوى القطع ،هندسية العدة ودرجة

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الحرارة.تم محاكات ثلاث انواع من نماذج اجهاد انسياب المشغولة وهي Oxley , Johnson-Cook and Zerilli –Armstrong ومقارنة النتائج المحاكات مع النتائج العملية الموجود في الادبيات . اظهرت نتائج المحاكات ان نموذج اجهاد الانسياب له تاثير رئيسي في النتائج .حيث ان نموذج Oxley يعطي اكثر دقة في حساب شروط القطع رغم الخطا في نتائج حساب زاوية القص وقوة الحرث اكثر من النموذجين الآخرين

INTRODUCTION

Metal cutting processes are widely used to remove unwanted material and achieve dimensional accuracy and desired surface finish of engineering components. In metal cutting processes, the unwanted material is removed by the cutting tool, which is significantly harder than the workpiece. The width of cut is usually much larger than the depth of cut and thus, the chip is produced in a nearly plane strain condition Importance of metal cutting operations may be understood by considering the total cost associated with this activity. For example, in the USA, the yearly cost associated with metal removal has been estimated at about 10 percent of the gross national product. The importance of the cutting process may be further appreciated by the observation that nearly every device in use in our complex society has one or more machined surface. Therefore, there are several reasons for developing a rational approach to material cutting[1]:

1. Improve cutting: Even minor improvements in productivity are of major importance in high volume production.

2. Produce products of greater precision and of greater useful life.

3. Increase the rate of production and produce a greater number and variety of products with the tools available.

In this paper, ***DEFORM-2D™*** software is used to simulate the turning process, which is based on the Lagrangian equation

.The software is used to simulate the effects of work piece flow stress on cutting variables such as cutting forces, chip geometry and temperature are investigated by comparing simulation results with experimental results available in the literature.

The use of FEM has become increasingly popular due to the advancement in computers and the development of complex codes.[2].

There are numerous studies on FEA of orthogonal cutting which provides essential information about the mechanics of cutting. This will be very useful for process planners and tool designers to optimize cutting conditions and materials prior to actual production.

The force, temperature and stress information provided by the FEA may be used to predict tool wear and according to this information the existing cutting conditions may be altered, if necessary, in order to prolong tool life. The geometry of the cutting tool, workpiece and cutting tool material properties, and tool-chip friction conditions must be defined carefully to obtain reasonable results from finite element .

Columbus [3] introduced ***DEFORM-2D™*** code that has been commonly used by researchers and industry in machining simulation. Applications of FEM models for machining can be divided into six groups**: a)** tool edge design, **b)** tool wear, **c)** tool coating, **d)** chip flow**, e)** burr formation and **f)** residual stress and surface integrity. The direct experimental approach to study machining processes is expensive and time consuming. For solving this problem, the finite element methods are most frequently used.

Yung-Chang Yen[4] discusses the numerical implementation of the integration of tool wear models with FEM calculations to predict the evolution of wear over long cutting periods.

For the estimation of tool wear rate for an uncoated carbide tool in cutting carbon steel, the Usui's wear rate model, based on adhesive wear. The simulations using a cutting tool with constantly updated rake face and flank face geometries have shown that it is possible to predict the evolution of tool wear at any given cutting time from FEM simulations by using the methodology proposed in this study.

The ultimate goal is to enable the complete construction of tool wear curves (i.e. VB versus cutting distance or time) and estimate the tool life through a FEM-based technique.

W. Grzesik, [5] Introduced FEM simulation model in order to obtain numerical solutions of the cutting forces, specific cutting energy and adequate temperatures occurring at different points through the chip/tool contact region and the coating/substrate boundary for a range of coated tool materials and defined cutting conditions. Commercial explicit finite element code Third wave Advant Edge [1] has been used in simulations of orthogonal cutting processes performed by means of uncoated carbide and coated tools. The latter were equipped with progressively increasing number of thin layers including TiC, TiN and Al2O3 films deposited onto ISO P20 carbide substrates. The result show a good agreement between predicted and experimental values of cutting temperatures, for uncoated and three-layer coated tools.

***Jaharah A.G[*6**]** Finite element method (FEM) in simulating the effect of cutting tool geometries on the effective stress and temperature increased in turning AISI 1045 .show The minimum temperature of 605°C on the cutting edge is obtained using rake and clearance angles of -5° and 5° respectively with cutting speed of 100mm/min, and feed rate of 0.15mm/rev.

The minimum effective stress of 1700MPa is achieved using rake and clearance angles of 5°and 5° respectively with cutting speed of 300mm/min, and feed rate of 0.25mm/rev.

WORK MATERIAL CONSTITUTIVE MODELS.

One of the most important subjects in metal cutting simulation is the modeling flow stress of work piece material properly in order to obtain true results. Flow stress is an instantaneous yield stress and it depends on strain, strain rate and temperature and represented by mathematical forms of constitutive equations. Among others, the most widely used ones in metal cutting simulations are Oxley, Johnson-Cook and Zerilli-Armstrong material constitutive models.

Johnson and Cook Material Model.

Johnson and Cook (1993) developed a material model based on torsion and dynamic Hopkinson bar test over a wide range of strain rates and temperatures. This constitutive equation was established as follows:

$$\sigma = (A + B\varepsilon^{n})\left(1 + CLn\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{0}}\right)[1 - \left(\frac{T-T_{r}}{T_{m}-T_{r}}\right)^{n} \qquad \ldots\ldots (1)$$

The first parenthesis is elastic-plastic term and it represents strain hardening. The second one is viscosity term and it shows that flow stress of material increases when material is exposed to high strain rates. The last one is temperature softening term.

A, B, C, n and m are material constants that are found by material tests. T is instantaneous temperature, T_r is room temperature and T_m is melting temperature of a given material. Johnson-Cook material model assumes that flow stress is affected by strain, strain rate and temperature independently[7].

Oxley Material Model.

Oxley (1990) and his co-workers used power law to represent material flow stress for carbon steel as:-

$$\sigma = \sigma_{1}\varepsilon^{n} \qquad \ldots.. (2)$$

Where σ and ε are flow stress and strain, σ1 is the material flow stress at ε=1.0 and n is the strain hardening exponent. σ_1 and n depend on velocity modified temperature (T_{mod}) given by Macgregor and Fisher. T_{mod} is defined as.

$$T_{mod} = T(1 - v\log\frac{\dot{\varepsilon}}{\dot{\varepsilon}_{o}}) \qquad \ldots.(3)$$

Where: ν and $^{0}\varepsilon$ are work piece material constants and they have values of 0.09 and 0.1for carbon steel[8].

Zerilli And Armstrong Material Model

Zerilli and Armstrong (1987) developed two micro structurally based constitutive equations. They worked on face-centered cubic (f.c.c.) and body-centred cubic (b.c.c.) metals to analyze their temperature and high strain rate responds and noticed a significant difference between these materials.Therefore, they developed two distinct models. The constitutive equation for b.c.c. metals can be written as follows:

$$\sigma = C_{\circ} + C_1 \exp\left(-C_3 T + C_4 T \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) + C_5\, \varepsilon^n \qquad \text{…. (4)}$$

Flow stress for f.c.c. metals is defined as

$$\sigma = C_{\circ} + C_2\, \varepsilon^{-1/2} \exp\left(-C_3 T + C_4 T \ln \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \qquad \text{….. (5)}$$

In these equations, C0 is component of stress that accounts for dislocation density on the flow stress, C1 - C5, n are material constants and T is the absolute temperature. In Equation 4, it is assumed that the strain dependence on flow stress is not affected by strain rate and temperature while it is opposite in Equation 5.

FRICTION MODELS

Friction modeling plays significant role on results such as cutting forces, temperature and tool wear in metal cutting simulation. Hence, researchers focused on determining a friction model to represent the real behavior of process. The most widely used ones in metal cutting simulation can be listed as follows.

Constant Coulomb

In early metal cutting simulation, the simple Coulomb friction model was used on the whole contact zone with a constant coefficient of friction. This model is defined as

$$\tau = \mu\, \sigma_n \qquad \text{….. (6)}$$

Here, τ is the frictional stress, σn is the normal stress and μ is the coefficient of friction.

In this study ,three simulations are carried out with using same friction model(Constant Coulomb) and coefficient. Friction coefficient is calculated by Equation(7) [stephen] .

$$\mu = \frac{F}{N} = \frac{F_p \sin\alpha + F_Q \cos\alpha}{F_p \cos\alpha - F_Q \sin\alpha} = \frac{F_Q + F_p \tan\alpha}{F_p - F_Q \tan\alpha} = \tan\beta \qquad \text{….. (7)}$$

From table 4
F_Q=600 and F_p= 745
substitute in equation 7
Friction coefficient = 600/745= 0.8

MODELLING USING THE FINITE ELEMENT METHOD

DEFORM-2D software is used to simulate the turning process, which is based on the Lagrangian equation . The software is used to simulate the effects of the flow stress model on cutting force, shear angle ,chip thickness, temperatures , tool wear , effective strains and stresses in machining of AISI 1045 steel using uncoated carbide inserts .

Tool Modeling

In analysis, cutting tool is assumed to be a rigid body. Geometric variables of the tool are given in Table1. Tool material was selected uncoated tungsten carbide (WC). Thermal and mechanical properties of WC are given in table 2 .

Table (1) Geometric variables of the cutting tool [10]

Rake angle	**Clearance angle**	**Tip Radius**
0 deg	4 deg	0.05 mm

Table (2) Thermal and mechanical properties

Elastic Modulus, E (MPA)	650000
Poisson's Ratio	0.25
Thermal Expansion (1/℃)	5.10^{-6}
Thermal Conductivity (N/sec/℃)	50
Heat Capacity (N/mm2 ℃)	4

Finite element mesh of tool is modelled using 820 nodes and 767 elements. Iso-parametric quadrilateral elements are used for the analysis. The distribution of mesh on tool is not uniform. Mesh density of tool tip and a part of rake face are modelled high with using mesh windows in the software to obtain more accurate temperature distribution results. This design is shown in Figure 1,2 .

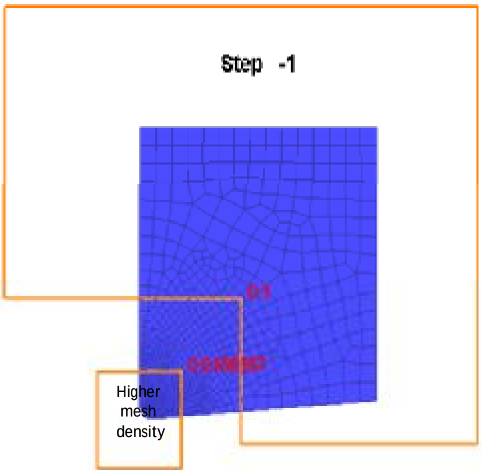

Figure (1) Mesh design of the tool

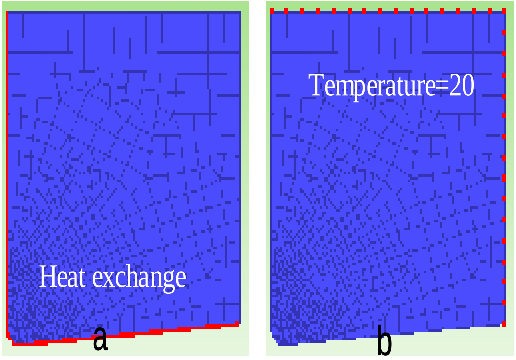

Figure (2) Cutting tool boundary condition

Boundaries by red colour in fig 2a. Red colour boundaries are sufficiently away from cutting edge therefore their temperature is fixed 20 ºC in fig 2b.

Workpiece Modeling

Flow stress modeling of work piece material is very important to achieve satisfactory results from metal cutting simulation. In the analysis, AISI 1045 is selected as work piece material. Oxley, Johnson-Cook and Zerilli-Armstrong material constitutive models are used to model the plastic behavior of AISI 1045. Due to high strain, strain rate and temperature in metal cutting, the material data is represented by flow curves at 11 different strain (0.05, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5), 7 different strain rates (1, 10, 100, 1000, 10000, 100000, 500000 s^{-1}) and 7 different temperature (20, 100, 300, 500, 700, 900, 1200 ºC) Examples of flow curves for each material constitutive model are shown in Figure 3,4,5,6,7,8

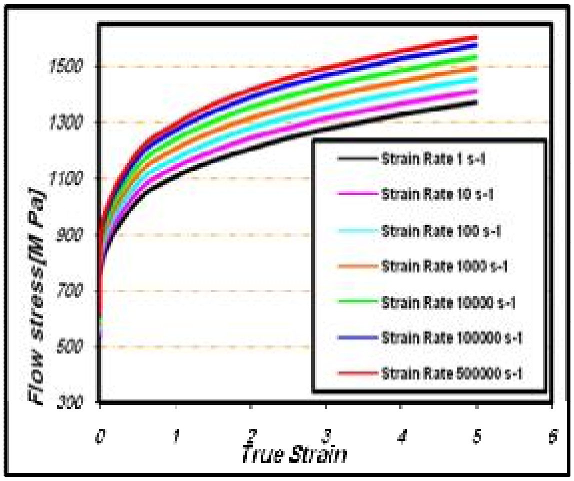

Figure (3) AISI 1045 Cook flow curve at T=20C 900900^{0}C

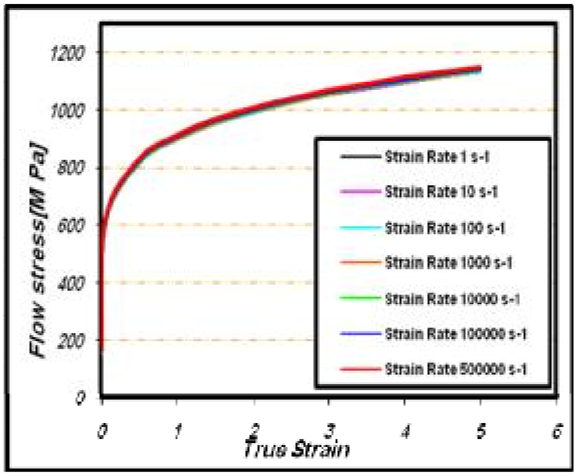

Figure (5) AISI 1045 Zer flow curve at T= 1200^{0}C.

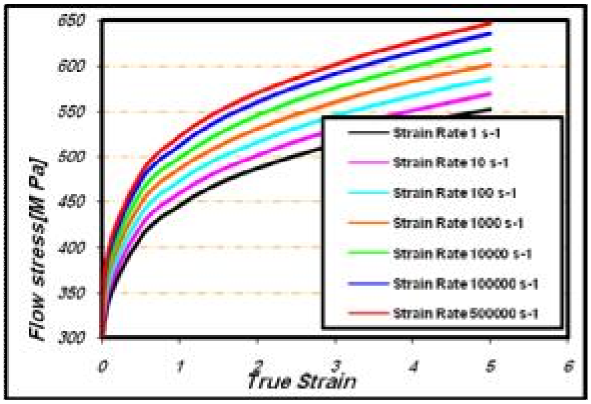

Figure (4) AISI 1045 Cook flow curve at T= 900^{0}C.

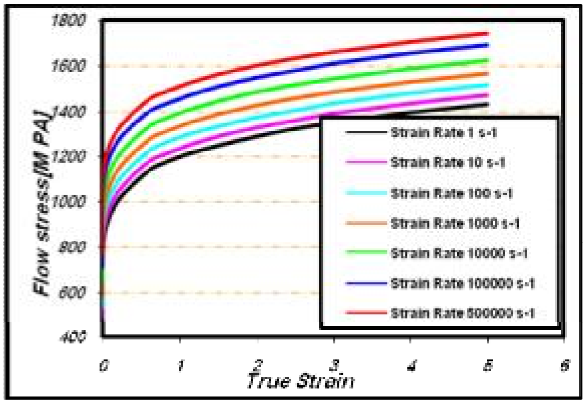

Figure (6) AISI 1045 Zer flow curve at T= 20^{0}C.

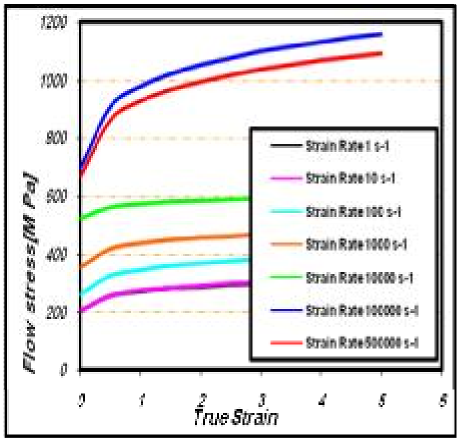

Figure (7) AISI 1045 Oxley flow curve at T= 900^{0}C

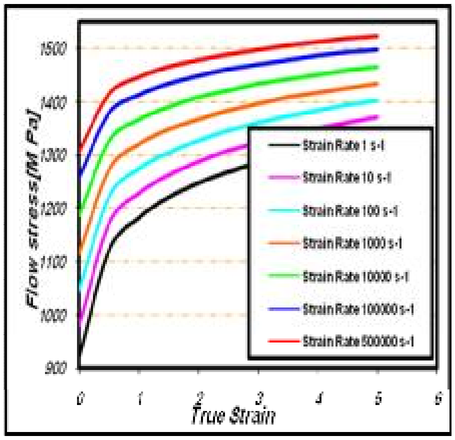

Figure (8) AISI 1045 Oxley flow curve at T= 20^{0}C

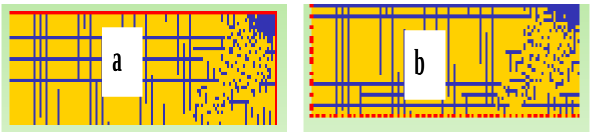

Figure (9) Mesh and Boundary Condition of Work piece.

During analysis, it is assumed that work piece does not undergo elastic deformation and it is allowed to show only plastic behavior. Finite element mesh of work piece is modelled using 1970 nodes and 1838 iso parametric quadrilateral elements . Heat exchange is defined on red color in fig 9.a .and The rest is fixed at20 ºC. Referring to fig 9.b, the base of the workpiece was constrained in x,y directions

When element distortion is detected, mesh generation is started as shown in Figure 10. Remeshing module will divide the contact boundary, add up suitable internal node or smooth elements and then interpolate stress, strain data for new mesh. As a second, plain strain assumption is made.

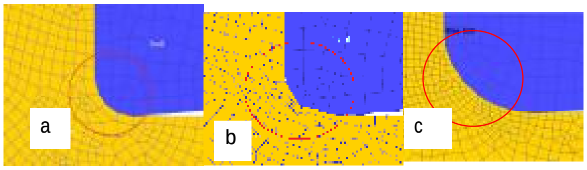

Figure (10) Enmeshing procedure at cutting zone ;
(a)Initial mesh distribution ;(c) New mesh genera tin

In addition to plastic properties of work piece, its thermal properties depending on temperature have to be given to the software for heat transfer calculation. Thermal conductivity, thermal expansion and heat capacity of AISI 1045 are shown in Figure 8,9,10 and 11.

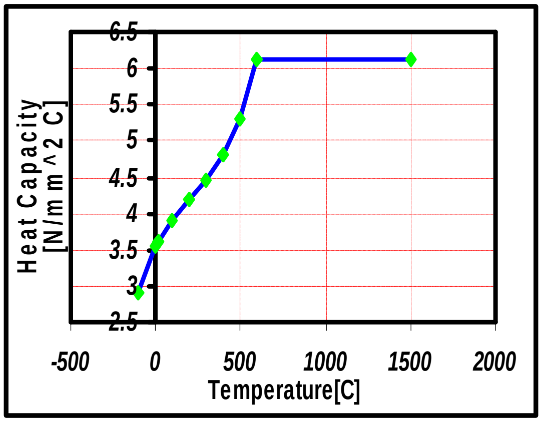

Figure .11 Heat Capacity of AISI 1045

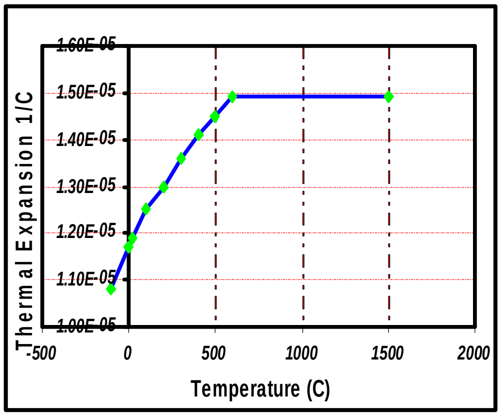

Figure .13 Thermal Expansion of AISI 1045

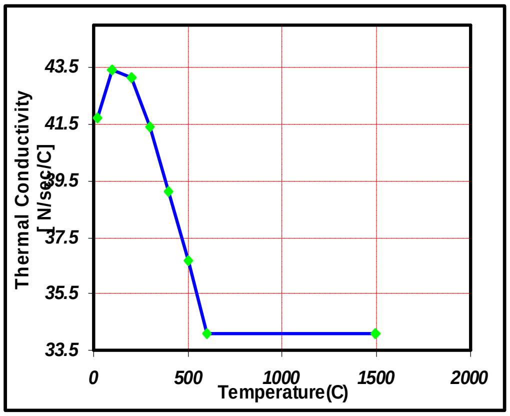

Figure .12 Thermal Conductivity of AISI 1045

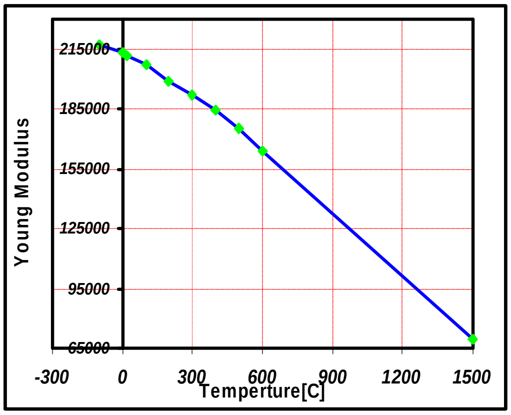

Figure .14 Young's Modulus of AISI 1045

CUTTING CONDITIONS

After modelling metal cutting components one by one, the next step is to assembly them due to cutting conditions. Cutting conditions are shown in Table (3).

Table (3) Cutting Conditions [10]

Cutting Speed (m/min)	Feed rate(mm/mm)	Width of cut(mm)
100	0.1	3

RESULTS AND DISCUSSION

The results of finite element simulations are presented. simulation results and experimental results available in the literature are compared. Experimental results are given in Table 4. as follows;

Table (4) Experimental results[10]

Cutting Force, Fc (N)	745
Thrust Force, Ft (N)	600
Chip thickness, tc (mm)	0.29
Shear Angle, Ø (º)	19
Temperature, T (ºC)	542

Comparison Of Material Constitutive Models

Comparison of Predicted Cutting and Thrust Forces.

The predicted values were taken from the quasi-steady state zone of the *Force vs. Time* curve fig 15. As mentioned, three different constitutive models are used in this study. Three simulations are carried out with using same friction model and coefficient. Friction coefficient is equal to 0.8. Effect of material constitutive models on cutting and thrust force is given in fig 16,17. It can be stated that Oxley model can predict cutting force more accurate in contrast to other two. All models overestimate cutting force. Thrust force is underestimated when using Oxley and Johnson-Cook models. However, it is overestimated when using Zerilli-Armstrong model. It can be seen that cutting and thrust forces are depending on flow stress models. Some error occurred in the analysis when calculating forces.

The differences between the experimental and predicted cutting force may be attributed to rigid tool and simplified friction model with constant coefficient usage in simulations. Secondly, measurement errors in experiments may be taken into consideration. Above considerations are valid when discussing thrust force errors too.

Comparison of Temperatures.

Temperature predictions are shown in fig 18. Predicted temperature in metal cutting simulation is mainly affected by friction models, friction coefficients, interface heat transfer coefficient and accuracy of thermal parameters of tool and work piece. It can be stated that flow stress models can affect temperature predictions too. Oxley flow stress model is good agreement with the experimental value.

Comparison of Chip thickness and Shear Angle.

Fig 19,20,21 shows the results of chip geometry results. The predicted values were taken from the quasi-steady state zone of the *Chip Geometry vs. Time* curve fig 22. Chip thickness and contact length between the rake face of the tool and the work piece are best estimated when Zerilli-Armstrong model is used fig 23. Some error occurs in calculating Chip thickness and contact length when using Oxley and Cook models. Shear angle estimated by Johnson-Cook model is good agreement with the experimental value more than Oxley and Zerilli-Armstrong models**.**

CONCLUSIONS

Three different material constitutive equations, results of model are compared with the experimental data available in the literature. It is seen that flow stress models have a major effect on calculated results. the results of the simulations show that oxley material model is able to give more accurate results for used cutting conditions in the analysis, however errors in calculating shear angle and thrust force are higher than johnson-cook and zerilli-armstrong material models. The following remarks are concluded;

1-Different friction coefficients and models must be tried to obtain more accurate results from the simulations (future work) .

2-Oxley flow stress model predicts cutting forces well 6% (16.8% and 38% deviations of cook and zerilli models).

3-Cook flow stress model predicts chip thickness very well 0.0027% (-33% and 18% deviations of oxley and zerilli models).

4-Cook flow stress model predicts shear angle very well 0.02% (18% and -10% deviations of oxley and zerilli models)

5-Higher value for the heat transfer coefficient(1000 n/(s/mm/°c) must be tried to obtain more accurate results from the simulations (future work) .

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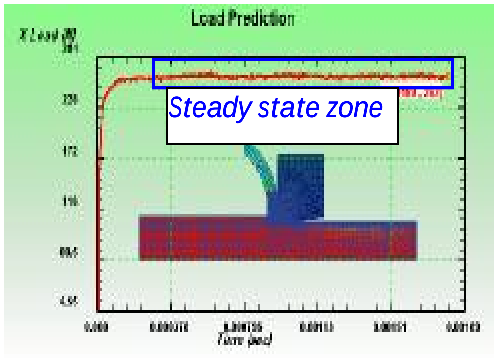

Figure (15) Example of predicted thrust force vs. time curve.

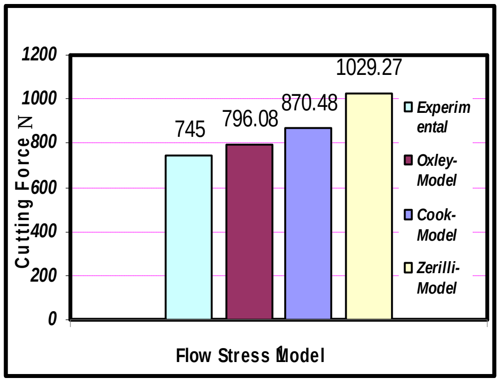

Figure (16) Cutting force vs. Flow stress model.

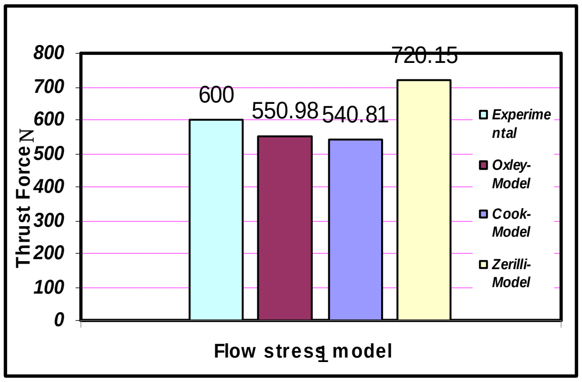

Figure (17) Thrust force vs. Flow stress model.

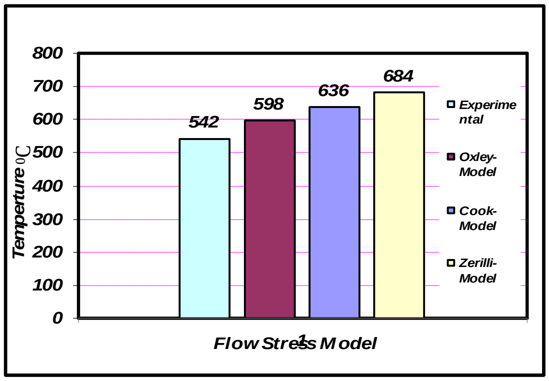

Figure (18) Temperature vs. Flow stress model.

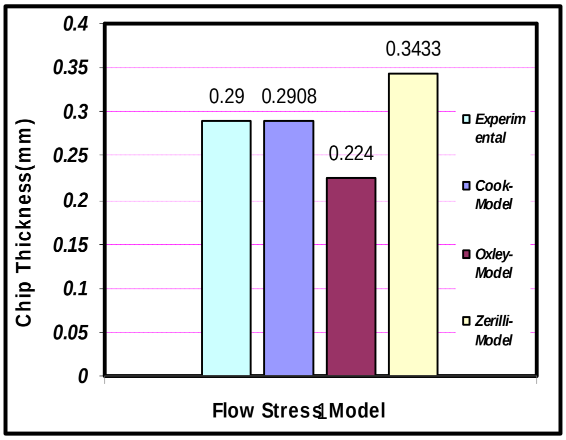

Figure (19) Chip Thickness vs. Flow stress model.

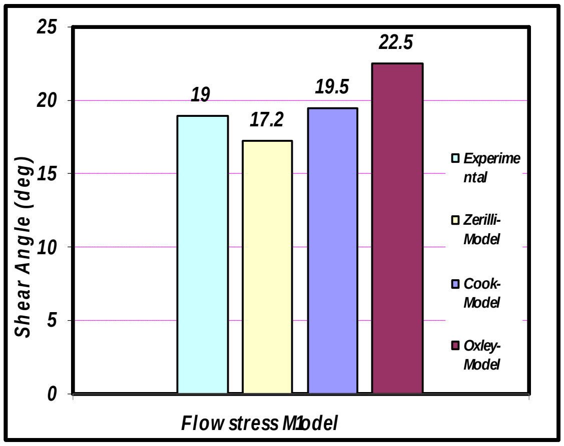

Figure (20) Shear angle vs. Flow stress model.

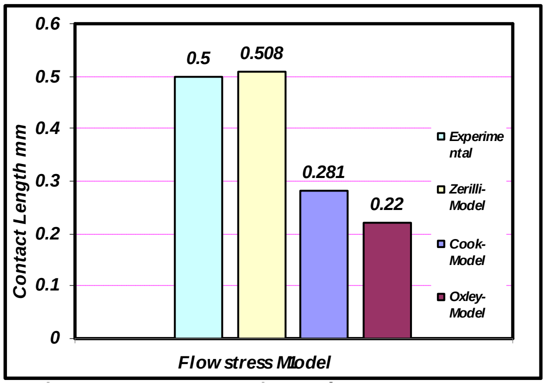

Figure (21) Contact Length vs. Flow Stress Model.

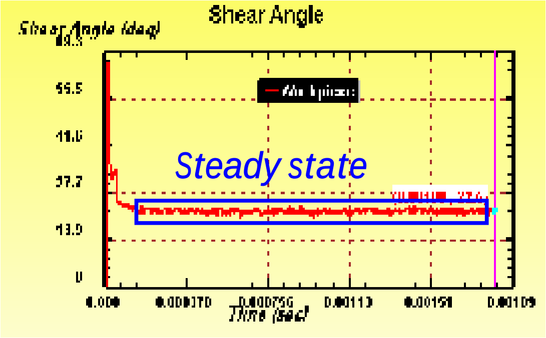

Figure (22) Example of predicted Shear Angle vs. Time Curve.

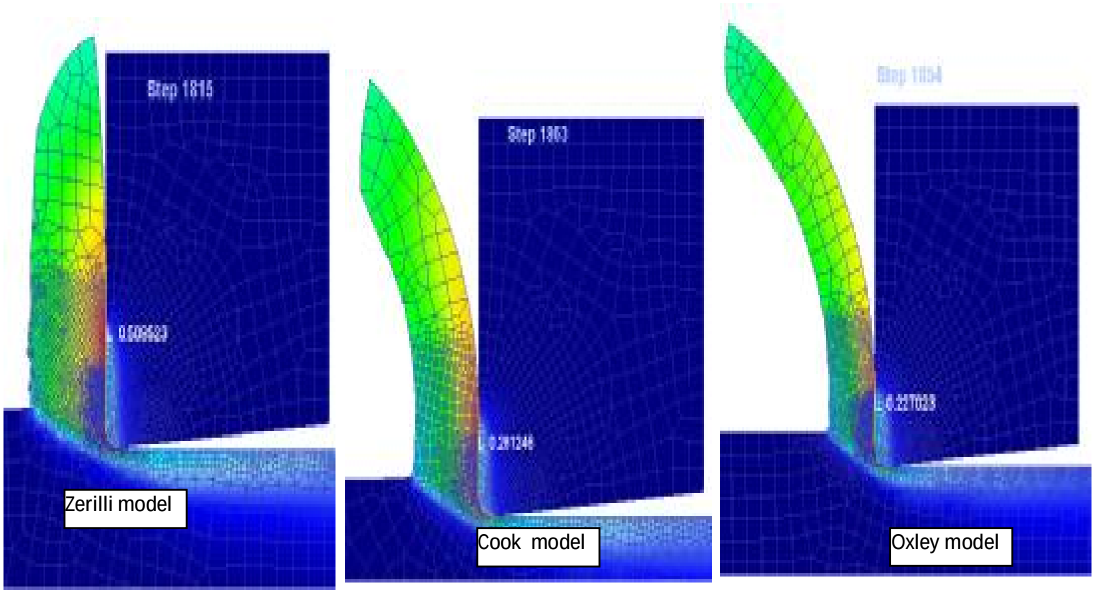

Figure (23) Estimated the Chip Thickness and Contact Length