FINITE ELEMENT ANALYSIS FOR PREDICTION OF CUTTING FORCES IN TURNING OF AISI 4340 STEEL

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Abstract- With the increasing demand for high quality, highly reliable, and economical machined components, the manufacturing industry must find innovative methods for producing precision components. To meet such demand, manufacturers are seeking ways to improve the process planning methodologies. One such method is machining simulation. This can be accomplished using Finite Element Machining analysis based on work flow stress models in order to simulate metal cutting processes. FEM based models are highly essential in predicting chip formation, computing forces, distributions of strain, strain rate, temperature, and stress in cutting zones. Johnson Cook's model gave constant value for each and every material and flow stress equation by using SHPB test. By an alternative tests such as Orthogonal test, tensile test and make use of Oxley's analysis flow stress calculated manually compared with JC's flow stress and comparison got varied linearly, hence proved that by an alternate tests flow stress will be calculated.

Keywords- turning, fuzzy controller, prediction, surface roughness

I. INTRODUCTION

In order to improve metal cutting processes it is necessary to model metal cutting processes at a system level. Advances in plasticity based analytical modeling and Finite Element Methods (FEM) based numerical modeling of metal cutting have resulted in capabilities of predicting the physical phenomena in metal cutting such as forces, temperatures and stresses generated. However, accuracy and reliability of these predictions depends up on a work material constitutive model describing the flow stress, at which work material starts to plastically deform. The present work provides a methodology to determine deformation behavior of work materials in high-strain rate metal cutting conditions.

The modeling and simulation of metal cutting have become very important in order to decrease the cost of experimental investigations. Continuum mechanics based Finite Element Methods (FEM) and plasticity based analytical modeling are used in predicting the mechanics of cutting such as forces, temperatures and stresses. These methods utilize and rely on work material constitutive models to simulate deformations conditions take place in metal cutting. Therefore, identification of constitutive material model parameters considering high-strain rate deformation characteristics is crucial. Empirical and semi-empirical constitutive models have been developed to model flow stress with certain accuracy in high-speed cutting. Most of these constitutive models are based on a range of assumptions in order to avoid the prevailing complexities in metal cutting. The success of a particular constitutive model depends on how effectively it represents physics of metal cutting as well as its ability to capture all relevant deformation parameters in a constitutive equation. In that respect, use of advanced computational methods and algorithms to determine most accurate constitutive models from the experimental data becomes highly critical and important.

The objective of this work is to explore and recalculate the parameters of the constitutive model determined by using Non linear regression analysis and investigate the effects of high-strain rate dependency, thermal softening and strain rate- temperature coupling on the material flow stress.

II. CONSTITUTIVE MODELS OR WORK MATERIAL FLOW STRESS

Metal cutting is the major manufacturing operation today in view of the economic significance. A fundamental knowledge of the metal cutting process is essential to find optimum conditions. Analytical and numerical models can be deduced from this fundamental knowledge to predict variables of interest for increasing process efficiency and part quality. Present work provides a methodology to determine the flow stress at high deformation rates and temperatures that are encountered in the cutting conditions

2.1. Johnson Cook Model

There are various work material flow stress models at present, the most satisfactory results is through Johnson Cook's model. To apply Johnson Cook's model to cutting process modifications are to be done using Oxley's analysis which utilizes modified Slip Line Field theory called Parallel Sided Shear zone theory in orthogonal cutting process. A non linear regression analysis is then used to obtain the Johnson Cook's constants from Orthogonal cutting experiment. These constants are substituted in the equation to obtain the required constitutive model. A flow stress model named Johnson-Cook constitutive model based on process dependent parameters such as strain, strain-rate and temperature was used to predict metal cutting conditions.

$$\sigma = [A+B\varepsilon^{n}]\,[1+C\ln(\acute{\varepsilon}/\varepsilon_0)]\,\{1-[(T-T_0)/(T_m-T_0)]^{m}\} \quad (2.1)$$

For the model to be applicable at cutting conditions Oxley's analysis is used to find the constants of the above equation. Using this analysis the model can be applied to machining regimes. High-speed cutting experiments and process simulations were utilized to determine the unknown parameters in flow stress model. Orthogonal cutting experiments were also used to verify the compatibility of the present work for the machining conditions. The model could be directly applied to Finite Element Machining Analysis in order to simulate metal cutting process.

In the Johnson-Cook constitutive model as given in Eq. (2.1), the parameter A is the initial yield strength of the material at room temperature. The equivalent plastic strain rate ε_0 is normalized with a reference strain rate ε_0. T_0 is room temperature, and T_m is the melting temperature of the material, and they are constants. While the parameter *n* takes into account the strain hardening effect, the parameter *m* models the thermal softening effect and *C* represents strain rate sensitivity. The Johnson- Cook model is a well-accepted and numerically robust constitutive material model and highly utilized in modeling and simulation studies.

An experiment is conducted with tensile testing machine on the work piece material and the values of stress and strain are recorded. The flow stress values obtained from the constitutive model are compared with experimental results. The comparison is satisfactory.

2.2 Orthogonal Cutting Model

Orthogonal cutting' is a term that was coined to describe the case where the cutting edge of the tool is straight and normal to both the cutting and feed direction. Piispanen was the first to introduce a model to illustrate the orthogonal cutting process in the late 1930s. His so-called 'card model' involving 'block wise slip' depicted the work piece material being cut as a 'stack of cards', where thin lamella's are produced which slip against successive elements as the tool penetrates the work piece (Fig.1).
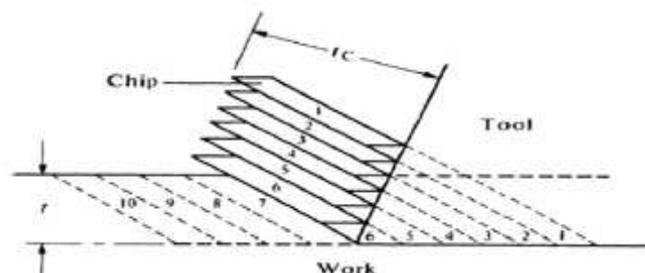

**Figure 1: Piispanen's 'card stack' model of chip formation**

2.3 Merchant's orthogonal force model

The well-known force model introduced by Merchant was based on the orthogonal cutting configuration and minimum energy principle, which states that the shear angle Φ will assume a value such that the total work done in cutting will be a minimum. Another assumption is that the shear strength of the material being machined is independent of the shear angle Φ, but equivalent to the shear stress acting on the shear plane. Based on the above suppositions, Merchant showed that the shear angle is related to the tool rake angle α and friction angle λ by Equation (2.2)

$$\Phi = [\Pi/4 - (\lambda-\alpha)/2] \quad (2.2)$$
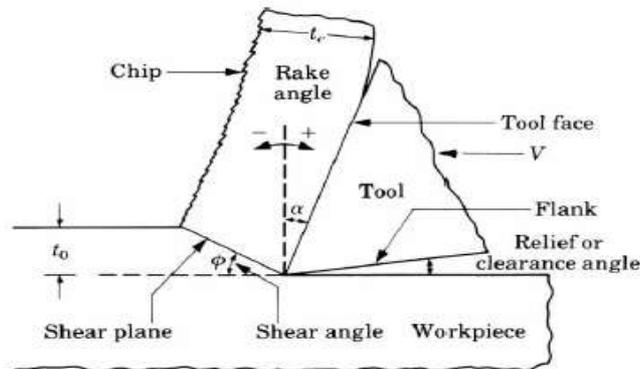
Figure 2: Idealized orthogonal cutting Model
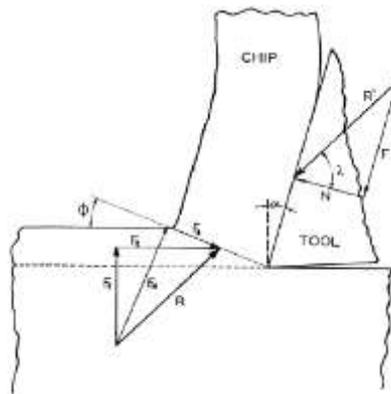
Figure 3: force system

2.4 Analytical model for orthogonal metal cutting

It is commonly recognized that the primary plastic deformation takes place in a finite-sized deformation zone. The work material begins to deform when it enters the primary deformation zone from lower boundary CD, and it continues to deform as the material streamlines follow smooth curves until it passes the upper boundary EF. There is also a secondary plastic deformation zone adjacent to the tool-chip interface that is caused by the intense contact pressure and frictional force.
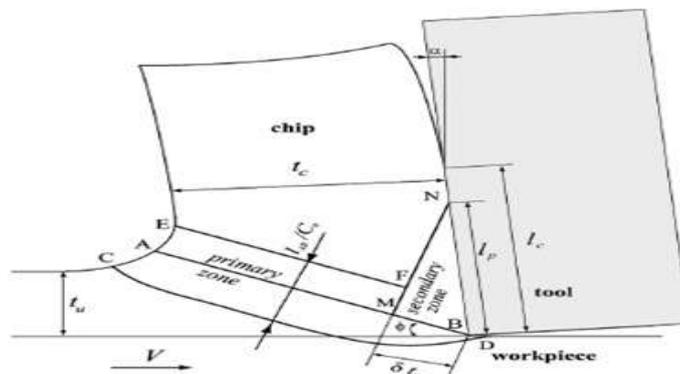
Figure 4: Simplified Deformation Zones in Orthogonal Cutting

After exiting from the primary deformation zone, some material experiences further plastic deformation in the secondary deformation zone. Using the quick- stop method to experimentally measure the flow field, Oxley proposed a slip-line field similar to the one shown in Figure 4. The slip-line field indicated that the strain rate in the primary deformation zone increases with cutting speed and has a maximum value at plane AB. Based on this experimental observations, he proposed the empirical relation in Eq. (3.8) for the average value of the shear strain rate along AB.

$$\dot{\gamma}_{AB} = C_0 (V_S / l_{AB}) \qquad (2.3)$$

The velocity along the shear plane is also given by Eq. (3.9).

$$V_S = \{ v \cos\alpha / [\cos(\Phi - \alpha)] \} \qquad (2.9)$$

Where, V is the cutting speed, α *the* rake angle, V_S the shear velocity and Φ is the shear angle.
Given by Eq. (3.8), l_{AB} is the length of AB, and C_0 is the material constant.
The shear angle Φ can be estimated from Eq. (3.10).

$$\Phi = \tan^{-1} \{ [(t_u/t_c)\cos\alpha] / [1- (t_u/t_c)\sin\alpha] \} \quad (3.10)$$

Where, t_u is the undeformed chip thickness, and t_c is the measured chip thickness.

$$\gamma_{AB} = \{ \cos\alpha / [2\sin\Phi \cos(\Phi - \alpha)] \} (3.11)$$

In the primary zone, the shear stress stays same on plane AB, and the average value of shear stress at AB is given by Eq. (3.12).

$$k_{AB} = [F_S \sin\Phi / (t_u \ w)] \quad (3.12)$$

Where w is the width of the chip, and the shear force F_S is calculated from the measured cutting force F_c and feed force F_T, as shown in Eq. (3.13).

$$F_S = [F_C \cos\Phi - F_T \sin\Phi] \qquad (3.13)$$

III. ASSESSMENT OF TEMPERATURE MODELS

Due to the difficulties associated with routinely measuring meaningful machining temperatures, developing mathematical models for machining temperature has been widely used as an attractive alternative. In Oxley's model, the average shear plane temperature T_{AB} is given by Eq. (3.14)

$$T_{AB} = T_0 + \{[(1-\beta) F_S \cos\alpha] / [\rho S t_u w \cos(\Phi - \alpha)]\}$$

$$(3.14)$$

where T_0 is the initial work piece temperature, the density ρ , S the specific heat value of the work material, β the fraction of the energy generated in the primary zone that enters in the work piece and determined by,

$$\beta = 0.5 - 0.35\log(R_T \tan\Phi) \quad \text{for } 0.04 \leq R_T \tan\Phi \leq 10.0$$
$$\beta = 03 - 0.15\log(R_T \tan\Phi) \quad \text{for } R_T \tan\Phi > 10.0 \ (3.15)$$

With R_T a non-dimensional thermal number given where K is the thermal conductivity of the work material by

$$R_T = [\rho S V t_u / K] \qquad (3.16)$$

The average temperature of the primary deformation zone can be estimated using Eq. (3.14). The average shear strain rate, shear strain, and shear stress in the primary deformation zone are given by Eqs. (3.8), (3.11) and (3.12), respectively. Using the Von Mises criterion, they can be related to the equivalent stress, strain, and strain rate using Eq. (3.17).

$$\sigma_{AB} = \sqrt{3}k_{AB} ; \ \varepsilon_{AB} = (\gamma_{AB} / \sqrt{3}) ; \ \dot{\varepsilon}_{AB} = (\dot{\gamma}_{AB} / \sqrt{3}) (3.17)$$

In order to determine the parameters of the JC constitutive model, a set of orthogonal cutting experiments is performed to measure the forces F_c and F_T in various cutting conditions and later values of σ_{AB}, ε_{AB}, $\dot{\varepsilon}_{AB}$ and T_{AB} are computed.

### 3.1 Experimental setup and predictive comparisons
In this work the experiments were conducted on a precision engine lathe. AISI 4340 alloy steel with diameter of 50 mm were selected as work piece material and the cutting tool is titanium coated indexable carbide cutting tool. A lathe tool dynamometer was used to measure the cutting

forces developed during cutting operation and also measures the temperature by using temperature gun. Comparison of Predicted average Temperature at tool chip interface with experiments. From orthogonal tests Tmax and Tmin are noted, These are the maximum and minimum temperatures obtained during the cutting operation at particular condition The two values are used because, the irregularities present in the material

Table1 : Experimental data from orthogonal cutting

Test	Tmin (^{0}C)	Tmax (^{0}C)	TAB (^{0}C)
1	33.6	59.2	46.6
2	34.8	57.6	46.2
3	40.9	45.0	42.96
4	44.1	46.2	45.52
5	38.9	53.9	46.42
6	39.9	59.9	49.87
7	40.6	46.1	43.38
8	30.6	50.6	40.95
9	40.1	46.9	43.52
10	45.9	45.3	45.60
11	46.1	50.5	48.21
12	43.8	49.1	44.74
13	43.1	59.6	49.25
14	46.6	48.7	47.68
15	46.5	51.7	49.25
16	47.5	49.1	48.32

| Test	N (rpm)	V (m/min)	t_u (mm)	t_c (mm)	F_c (N)	F_t (N)
1	180	28.27	0.1	0.26	16	4
2	180	28.27	0.2	0.32	18	6
3	180	28.27	0.3	0.38	26	10
4	180	28.27	0.4	0.48	33	13
5	280	43.98	0.1	0.26	13	7
6	280	43.98	0.2	0.3	15	9
7	280	43.98	0.3	0.42	30	13
8	280	43.98	0.4	0.42	35	14
9	450	70.69	0.1	0.3	26	13
10	450	70.69	0.2	0.33	25	12
11	450	70.69	0.3	0.36	30	14
12	450	70.69	0.4	0.42	34	15
13	710	115.52	0.1	0.22	10	7
14	710	115.52	0.2	0.32	17	9
15	710	115.52	SS	0.34	27	11
16	710	115.52	0.4	0.43	38	14
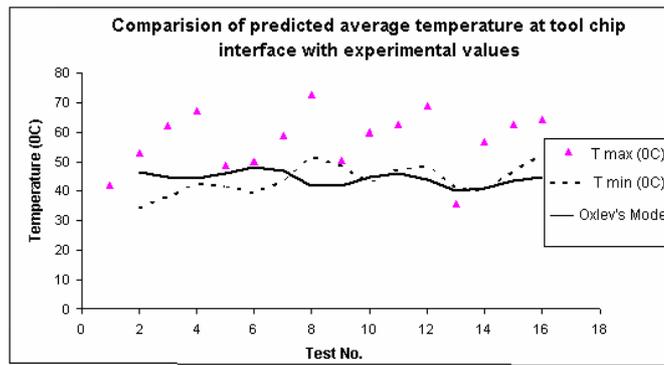
Figure 5: **Comparison of Predicted Average Temperature at Tool Chip Interface with Experimental Values**

## IV. COMPARISON OF PREDICTED STRESS VALUES WITH TENSILE TEST RESULTS
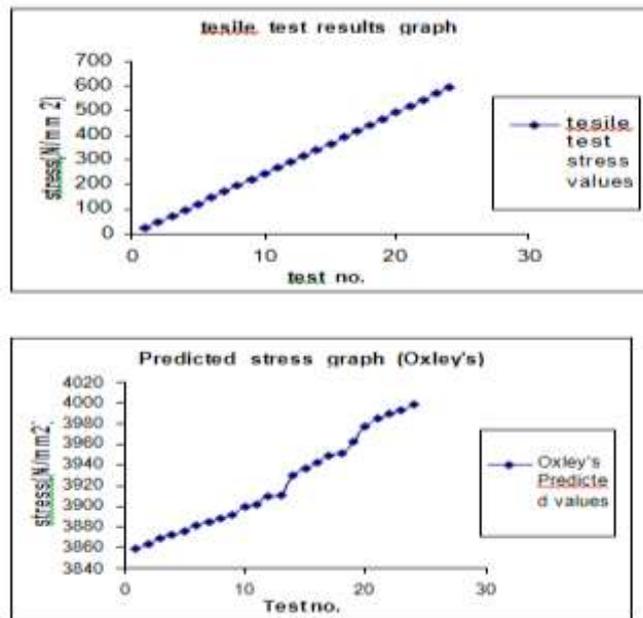

V. FEM ANALYSIS

Finite Element Analysis is a step by step procedure it includes different steps such as operation setup, insert setup, work piece setup, positioning, simulation control and data base generation. In this work we are used 2D deform package to predict the friction distribution at tool chip interface, stress distribution and temperature distribution at various cutting speeds and depth of cuts.
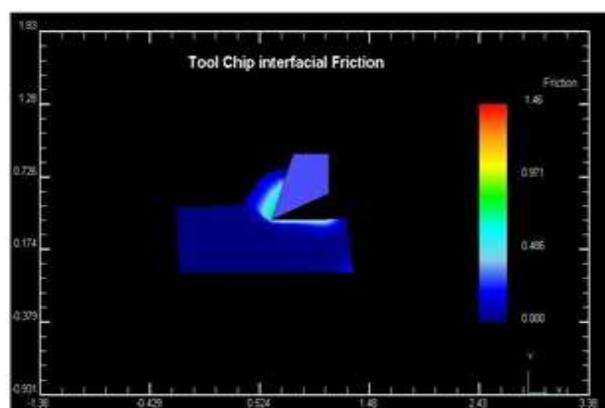
Figure 6: Friction distribution
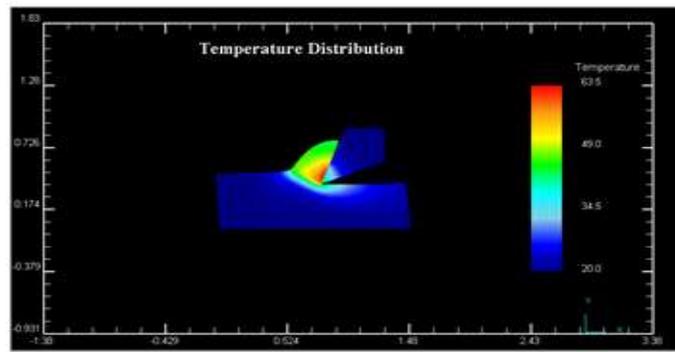
Figure 7: temperature Distribution
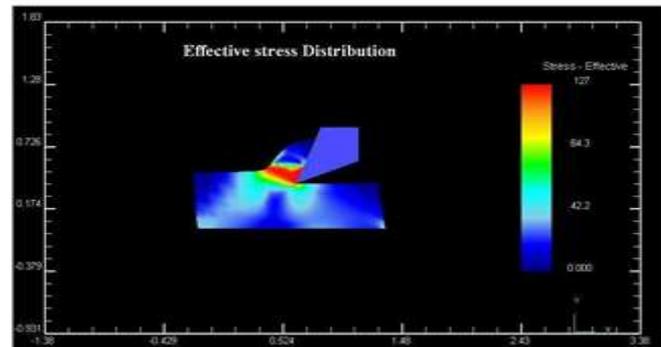
Figure 8: Effective stress distribution

VI. CONCLUSIONS

Present work utilizes an extended metal cutting analysis originally developed by Oxley and co-workers and presents an improved methodology to expand applicability of the Johnson-Cook material model to the cutting conditions. A number of cutting temperature models are also used in characterizing the accuracy of the average temperatures at primary deformation zone. Predictions using various temperature models are compared with the results of orthogonal cutting test data obtained for AISI 4340 steel through assessment of machining models. The temperature model introduced by Oxley is found to closely predict the average temperature in shear plane.

The extended Johnson-Cook work flow stress constants and tool-chip interfacial friction characteristics can be directly entered into most Finite Element Machining Analysis software.

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