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MODELING OF HIGH SPEED MACHINING PROCESSES FOR PREDICTING TOOL FORCES, STRESSES AND TEMPERATURES USING FEM SIMULATIONS

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Abstract

In this work, a methodology was developed to determine flow stress at high deformation rates and temperatures that are encountered in the cutting zone, and to estimate friction at the chip-tool interface simultaneously. Orthogonal cutting experiments were used together with FEM simulation of the cutting process. This technique was applied to machining of P20 mold steel (30 HRC) using uncoated carbide tooling. The friction at the chip-tool contact was estimated by using the flow stress data determined at high speed cutting conditions. This data was used in modeling of turning with nose radius cutting tools where the cutting process is simulated with plane strain and axisymmetric plastic deformation analysis. The resultant cutting forces, tool stresses and temperatures were predicted in the primary and secondary cutting edges accordingly. Furthermore, this technique was extended to modeling of cutting process in flat end milling using straight cutting edge inserts with nose radius corners.

1. INTRODUCTION

High speed machining (HSM) of hard alloy steels (up to hardness of 62 HRC) offers several advantages such as reduction of finishing operations, elimination of part distortion, achievement of high metal removal rates and lower machining costs as well as improved surface integrity [1]. However, HSM results in high temperatures and stresses at the tool-workpiece interface. Consequently, cost effective application of this technology requires a fundamental understanding of the relationships between process variables. Thus, it is necessary to understand how temperatures and stresses, developed during HSM, influence tool wear and premature tool failure (chipping of cutting edge) as well as residual stresses on machined surfaces.

Metal cutting process is not only a material removal process, but also a deformation process where deformation is highly concentrated in a small zone [2]. Thereby, it can be investigated as a chip formation process and simulated using Finite Element Method (FEM) techniques. The main advantage of such an approach is to be able to predict all process variables arisen in the deformation zones. However, material flow characteristics at the high temperature, strain-rate and strain, encountered during cutting process, are very important for predicting chip flow, cutting forces, temperatures and stresses. There is very few material data available for the deformation conditions that exist in machining. Flow stress data are mainly obtained by using impact compression tests for various materials at the moderate deformation rates [3]. However, further development is needed to overcome the uncertainty in the high temperature and strain rate material property data suitable for simulation of high speed cutting. Besides, the contact regions and the friction parameters between the chip and the tool are influenced by factors such as cutting speed, feed rate, rake angle etc., mainly because of the change in the normal pressure at the tool surface [4].

Earlier models of metal cutting were based on only basic shear plane assumption or slip line field analysis [5] [6]. On one hand, some researchers used numerical methods to estimate temperatures in the chip and the tool [7] [8]. On the other hand, others proposed analytical approaches to predict machining conditions and tool life supported by small number of experiments [9]. Later, models that include chip-tool contact friction and material behavior at high strains, strain-rates and temperatures were proposed [10] [2] and noteworthy attempts for FEM simulation of cutting processes were presented [11] [12] [13] [14] [15] [16] [17]. Analytical models as well as FE based model for chip flow and chip breaking were also well documented [18][19] [20]. A recent review of the technical literature reveal that currently FEA of machining is not fully capable of simulating 3-D machining operations due to the computational requirements [21]. However, present mechanistic models for analyzing metal cutting operations are still not fully able to determine temperatures and stresses at the tool with enough accuracy.

Recently, orthogonal cutting was also simulated using a software for large plastic deformations, DEFORM™, and chip formation for continuos and segmented chips were predicted using a fracture criteria [22]. Capabilities in generating a very dense mesh near the tool tip and remeshing adaptively makes this software applicable to simulate cutting process. Although the assumed input data for material properties and friction were quite approximate; simulation of metal cutting was carried out with relatively little effort [23]. These preliminary investigations demonstrated that with reliable input data on material properties it is possible to estimate chip flow and cutting forces. In addition, this model was also extended to simulate chip flow in 2-D flat end milling with straight cutting edges. The motion of the cutting edge that results in variable chip thickness was simulated and tool forces, stresses and temperatures were all predicted. In this case plane strain behavior was assumed and, therefore, 2-D simulations gave good agreements with the experimental results in chip shape and force predictions [24].

The main objective of the presented work was to develop a predictive model for the high speed cutting process using FEM simulations and to apply this model to (a) turning with nose radius tools and (b) flat end milling operations. Therefore, the present research is aimed at developing methods for estimating the distributions of temperatures and stresses on the tool surface in high speed machining of hard steels.

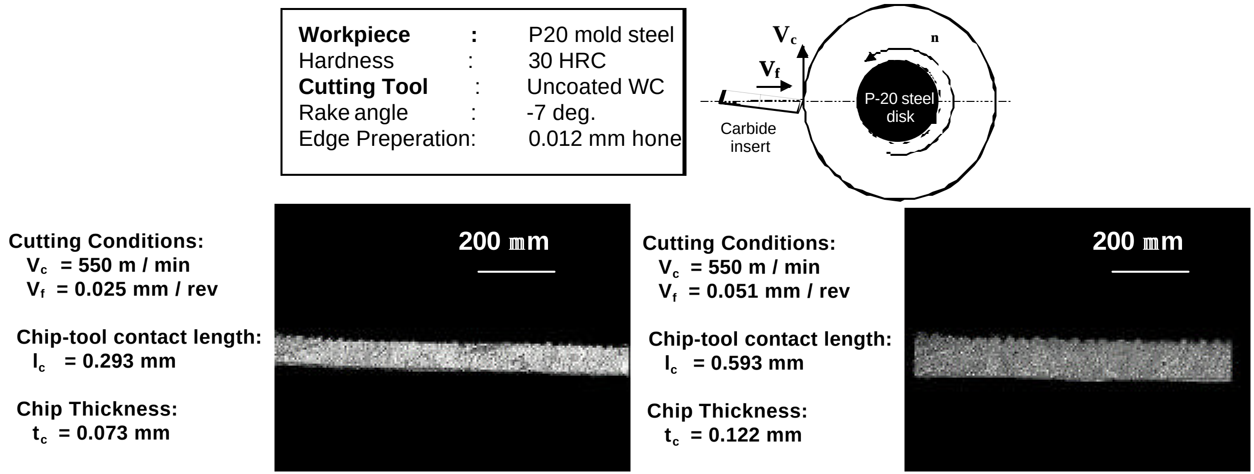
2. DETERMINATION OF FLOW STRESS AND CHIP-TOOL CONTACT FRICTION FOR HIGH SPEED MACHINING

In HSM, extremely high strain rates (about 1.67×10^5 sec^{-1} at 500 m/min cutting speed and 0.05 mm feed) and temperatures (about 1400 ^{0}C) at the chip-tool interface occur in the primary deformation zone and secondary deformation zone respectively. The material flow stress (yield strength of the workpiece material) behavior corresponding to these regimes is usually unknown [2]. In addition, the frictional conditions at the chip-tool contact become difficult to predict as both sticking and sliding frictions occur simultaneously between the chip and the cutting tool [11]. To address the issues of flow stress and friction, a methodology was developed for determining simultaneously both the flow stress of workpiece material and the friction conditions at the chip-tool contact interface (see Fig.1).

2.1 Methodology for Estimating Flow Stress and Chip-Tool Contact Friction

The basic concept of the proposed methodology is the use of orthogonal cutting experiments and FEM simulations in order to determine the flow stress and friction conditions used for the range of high speed machining. Therefore, a limited number of orthogonal end turning experiments on P20 mold steel disks (at hardness of 30 HRC) was conducted using uncoated tungsten carbide (WC) tooling (see Figure 1). From the experiments, two components of cutting force (F_c and F_t), chip thickness (t_c), and chip-tool contact length (l_c) were measured. Also, the microscopic pictures of chips were collected to identify chip formation.

In machining hard materials, continuous chip formation is observed at moderate feed rates. At higher feed rates a “saw tooth” or “shear localized” chips are produced, [25]. Thus, the conditions for formation of saw tooth type of chips were avoided by choosing small undeformed chip thickness (i.e. feed rates) in the orthogonal turning experiments (Fig.1).



Workpiece	:	P20 mold steel
Hardness	:	30 HRC
Cutting Tool	:	Uncoated WC
Rake angle	:	-7 deg.
Edge Preperation:		0.012 mm hone

Cutting Conditions:
V_c = 550 m / min
V_f = 0.025 mm / rev

Chip-tool contact length:
l_c = 0.293 mm

Chip Thickness:
t_c = 0.073 mm

Cutting Conditions:
V_c = 550 m / min
V_f = 0.051 mm / rev

Chip-tool contact length:
l_c = 0.593 mm

Chip Thickness:
t_c = 0.122 mm

Figure 1: Chip geometry measured from the experiments in orthogonal turning of P20 mold steel

Later, FEM simulations of continuous chip flow in orthogonal cutting process were conducted. The average strain, strain-rates and temperatures were computed both in primary (shear plane) and secondary (chip-tool contact) deformation zones (Fig.2). The flow stress data were iterated and FEM simulations were repeated until the prediction error for cutting force minimized. The friction conditions in sticking and sliding regions at the chip-tool interface are estimated using Zorev's stress distribution models as shown in Figure 3. The shear flow stress (k_{chip}) was also determined using computed average strain, strain-rate, and temperatures in secondary deformation zone, the friction coefficient (*m*) was estimated accordingly until the prediction error for friction force is minimized. Thereby, matching the measured values of the cutting forces with the predicted results from FEM simulations, a curve fitted flow stress equation and the friction parameters at the chip-tool contact are obtained.

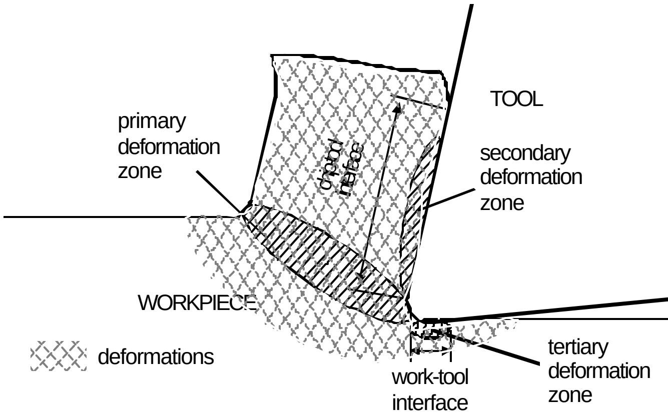


Figure 2: Deformation zones in orthogonal cutting

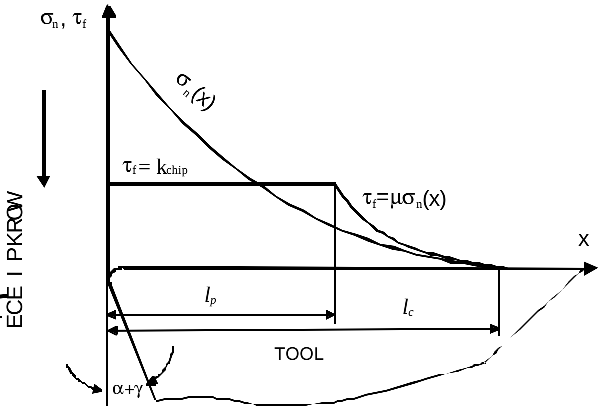


Figure 3: Friction model at chip-tool interface, after Zorev [10]

The flow stress data under machining conditions was represented with the following flow stress model [3]:

$$\bar{s} = K\left(e^{aT} + Ae^{b(T-T_0)^2}\right)\left(\frac{\dot{\bar{e}}}{\dot{\bar{e}}_R}\right)^c (\bar{e})^d \tag{1}$$

In Equation 1, $\bar{s}$ represents flow stress, and $\dot{\bar{e}}$, $\bar{e}$, T represent strain rate, strain, and temperature respectively. The specified parameter ($\dot{\bar{e}}_R$) is introduced to neutralize the units and the coefficients a, b, c, A, K, T_0 are computed by using least square parameter estimation.

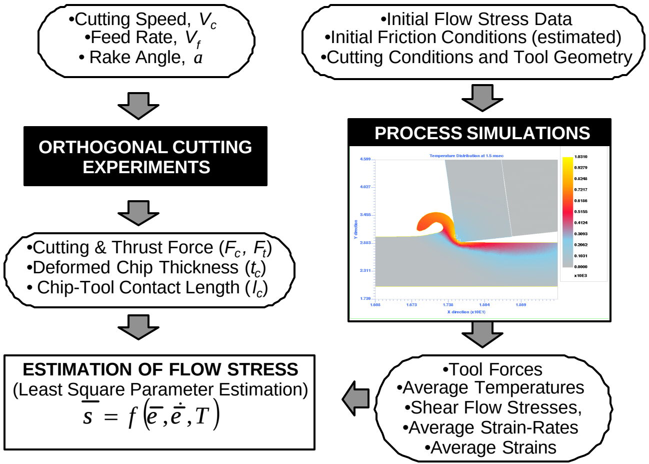


Figure 4: Methodology for determination of workpiece material flow stress and friction at chip-tool interface

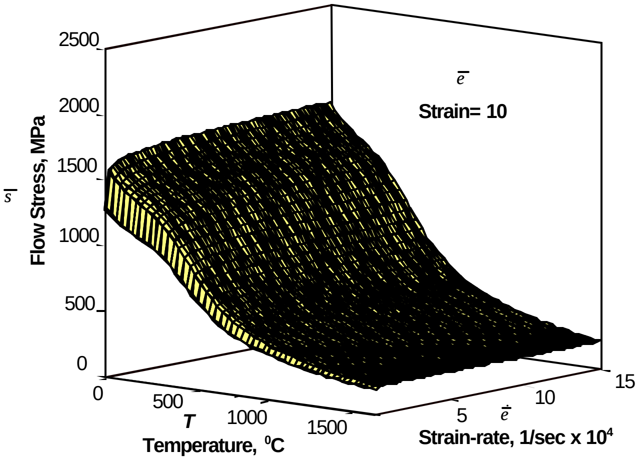
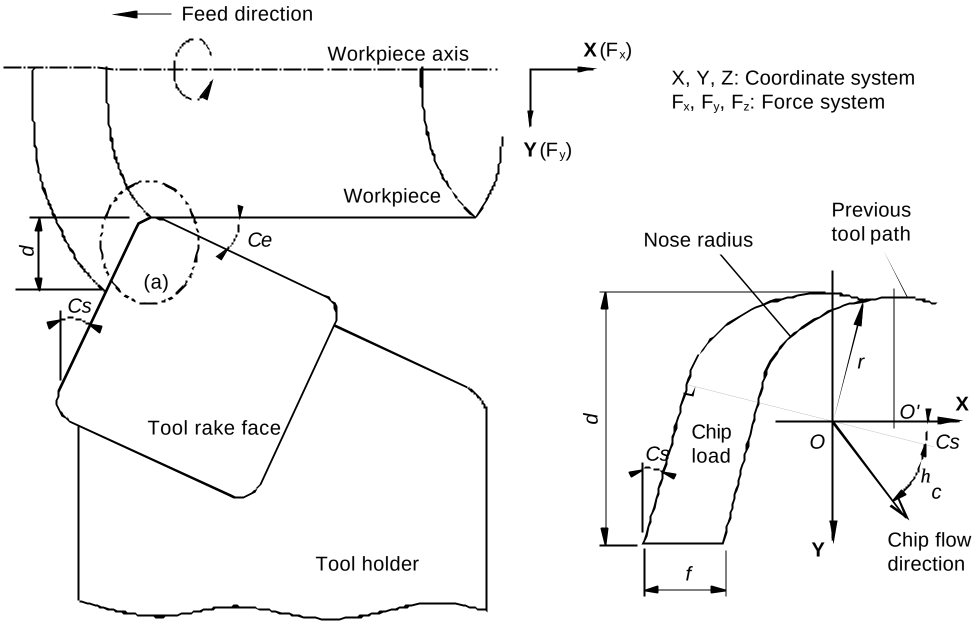


Figure 5: Flow stress determined from orthogonal cutting experiments using FEM simulations

3. MODELING OF TURNING PROCESS

Practical machining operations, such as turning and face milling, often involve cutting tools with two cutting edges and an included non-zero radius of the tool nose (Fig 6). In order to investigate the effects of tool nose radius on the cutting process, modeling of 3-D metal cutting processes with finite element technique is possible but requires extensive computational time and capacity with the existing workstations. Therefore, an alternative of process simulation using 2-D deformation models for predicting 3-D metal flow in cutting processes is considered. A similar approach was taken to predict tool forces in an earlier study [18].



(a) Tool tip detail

Figure 6: Schematic for turning process using tools with nose radius

In the past, it was suggested that the cutting forces (F_x, F_y, F_z) and chip flow angle (h_c) can be estimated through analytical models with simplified assumptions [26]; however, the cutting temperature and stress distributions may not be predicted without using numerical methods. Therefore, FEM based simulation techniques are most appropriate for estimating tool temperature and stress distributions, which is the main objective of the presented research.

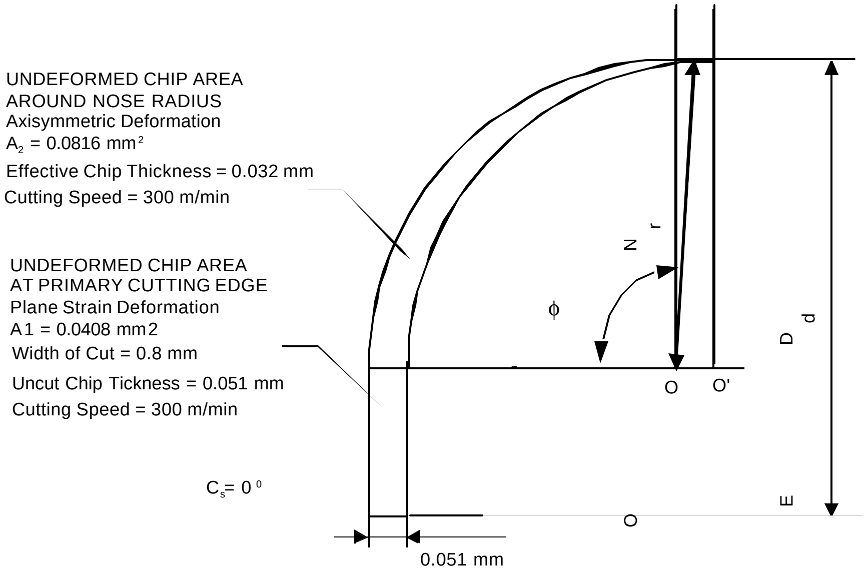


Figure 7: Undeformed chip geometry for turning process using tools with nose radius

A simple turning insert geometry with a nose radius of 1.6 mm, zero normal rake (α_n), inclination (*i*) and side cutting edge angle (C_s) was used. A depth of cut (*d*=2.4 mm) was selected to emphasize size effect due to increase in specific cutting forces. As shown in Figure 7, the deformation of workpiece and chip flow around the tool nose can be analyzed with two separate regions based on the cutting edge geometry. Equivalent chip load of 0.0321 mm was computed using the undeformed chip geometry (Fig 8). An axisymmetric chip load model was then applied on the chip elements along the nose radius whereas a plane-strain model of chip load was used for the elements with straight edge cutting. Finally, the orthogonal data of simulation for each chip element was coupled and the overall process variables were predicted accordingly.

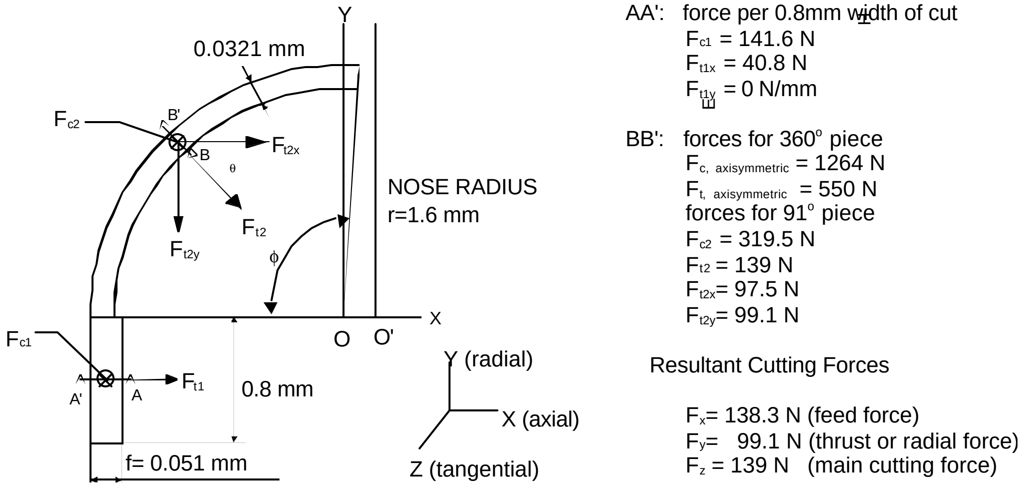


Figure 8: Prediction of tool forces in using FEM simulations (workpiece P20 steel at 30 HRC, cutting tool uncoated tungsten carbide)

In this analysis, the undeformed chip geometry around the nose radius was represented using only one equivalent chip element for axisymmetric deformation simulations. The number of equivalent chip elements around the nose radius can be increased to obtain more accurate results in predictions.

The predicted tool temperature distributions are calculated on the cross sections of AA' where a plane strain deformation model and BB' where an axisymmetric deformation model were used. Predicted chip flow and temperature distribution in the tool and the workpiece from FEM simulations are shown in Figure 9.

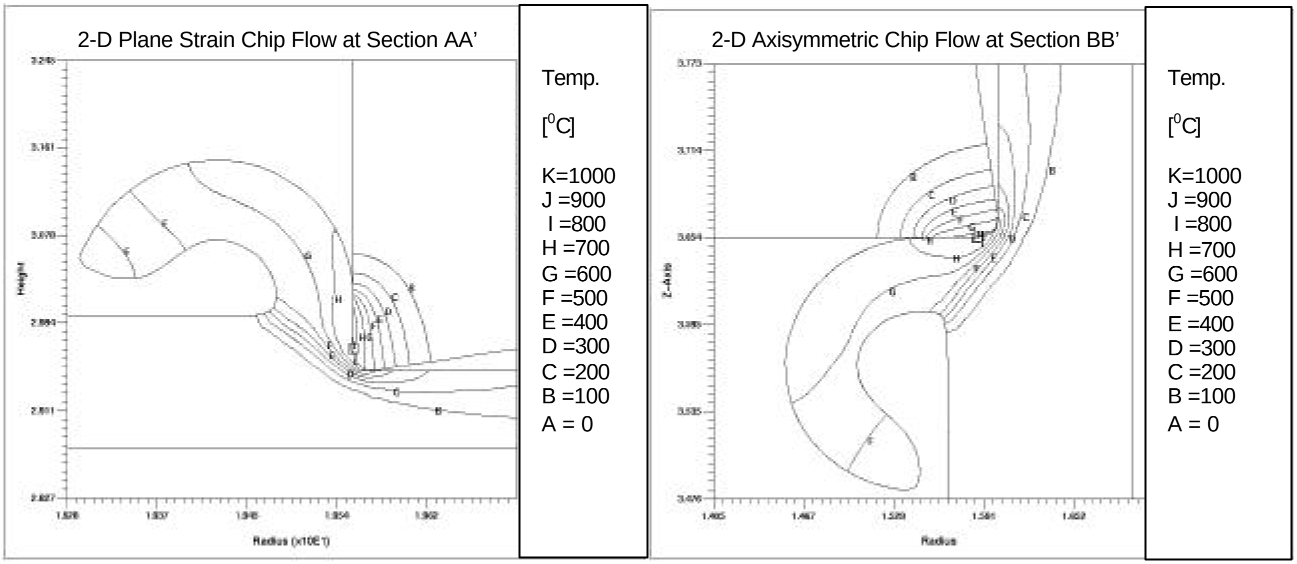


Figure 9: Predicted chip flow and temperatures in turning process using tools with nose radius insert

Similarly, the predicted distributions of the maximum principle stresses on the cross sections AA' and BB' are also given with Figure 10.

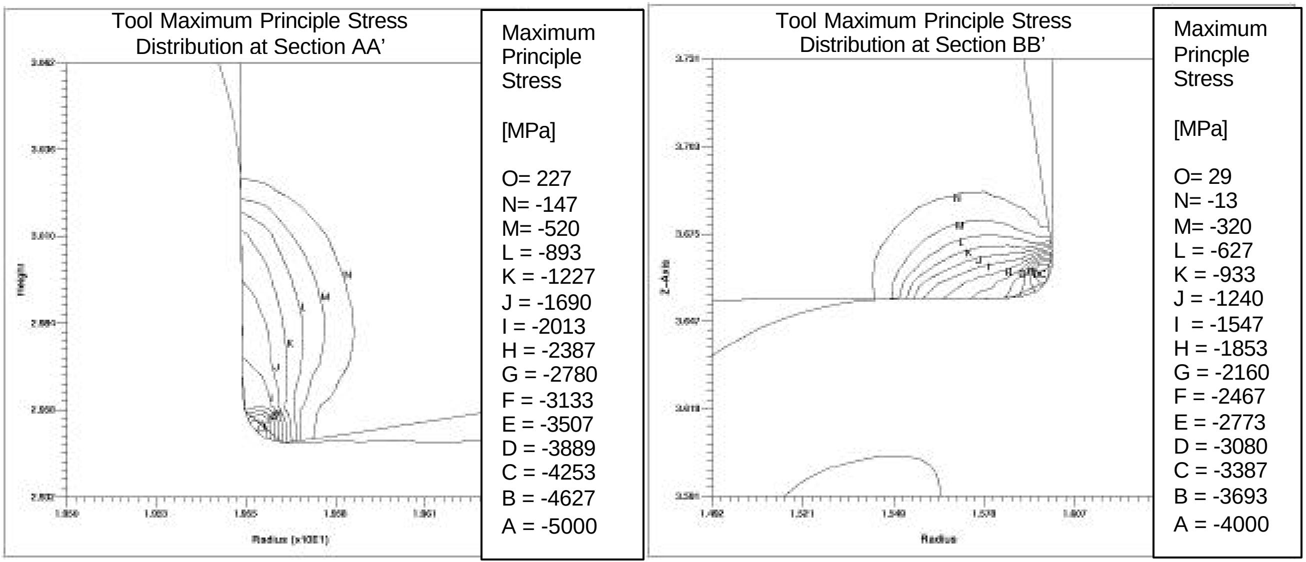


Figure 10: Predicted distribution of tool principle stresses in turning process with nose radius insert

4. MODELING OF FLAT END MILLING PROCESS

Similar to turning with a nose radius tool, flat end milling operation with indexable inserts also involves 3-D metal flow around the insert tip which has a non-zero radius. Some mechanistic models can predict the chip flow angle (η_c) and cutting forces generated (F_x, F_y, F_z) with the various depth of cuts (a_n, a_e) , feeds (f_z) and cutting speeds (V_c) after conducting a number of calibration experiments even for more complicated cutter geometries [27] [28] [30]. However, other process variables such as tool stresses and temperatures can not be predicted by using only mechanistic modeling.

In this study, flat end milling operation using a single insert indexable tool with a straight cutting edge (i.e. null helix angle) was selected to investigate the cutting process in milling as a simple example (Fig 13). Chip flow in dry milling of P20 mold steel using a uncoated tungsten carbide cutter was simulated for selected cutting conditions (cutter diameter: D = 15.88 mm, cutting speed: V_c = 200 m/min, feed: f_z = 0.1 mm/tooth, axial depth of cut: a_n= 2 mm, and radial depth of cut: a_e = 15.88 mm).

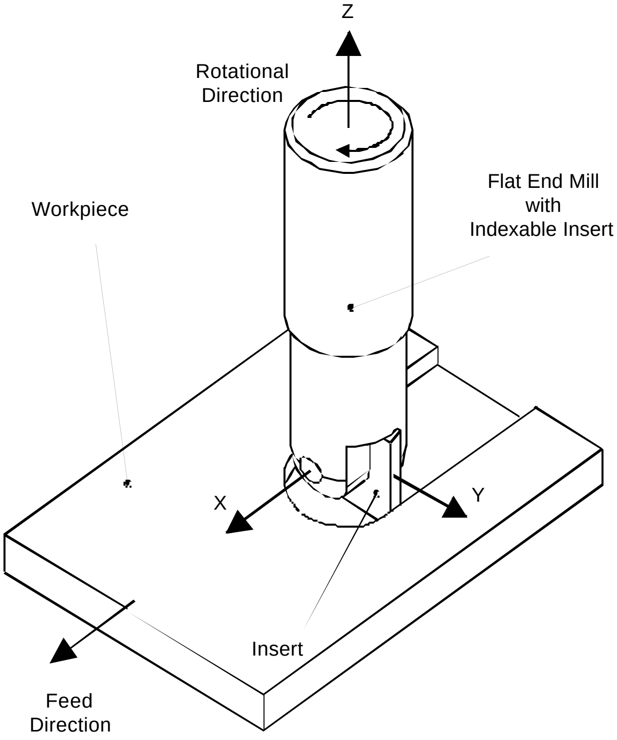


Figure 11: Schematic for slot milling using flat end mill inserts with nose radius

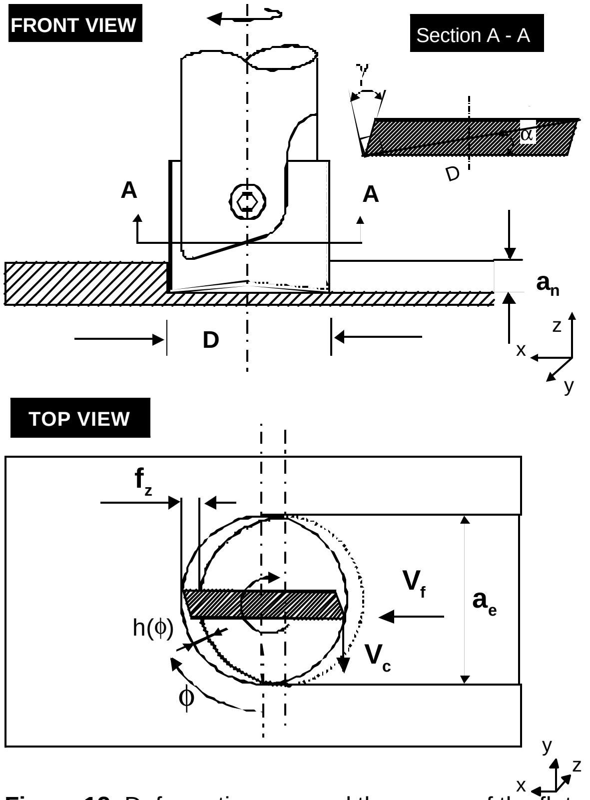


Figure 12: Deformations around the corner of the flat end mill inserts with nose radius

The chip deformation in flat end milling using insert with nose radius corners can also be investigated in two regions where plane strain and axisymmetric deformations take place (see Figure 12). This process can be modeled with 2-D FEM simulations of chip deformation and deformation models will be coupled in order to predict overall process variables.

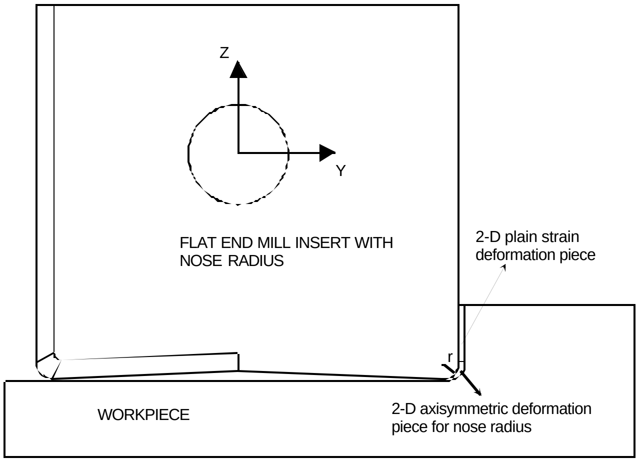


Figure 13: Schematic for slot milling using flat end mill inserts with nose radius

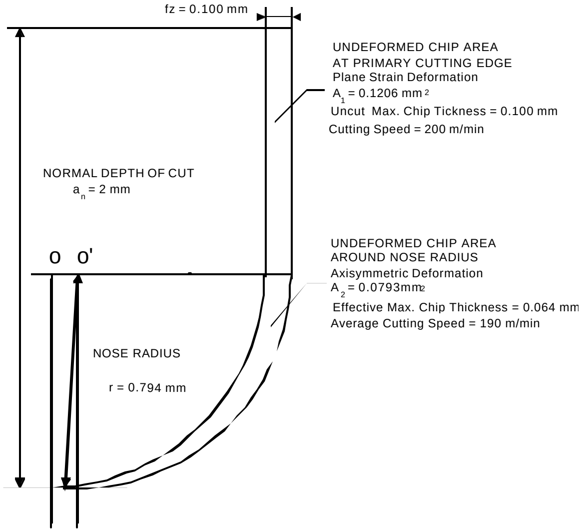


Figure 14: Schematic for slot milling using flat end mill inserts with nose radius

4.1 Modeling of 2-D Plain Strain Chip Flow in Flat End Milling

2-D plain strain chip flow was simulated to predict temperatures, tool stresses and cutting forces were predicted (Fig 15). Milling experiments were also conducted in a horizontal high-speed milling center (Makino A-55 with 14,00 rpm spindle and 40 m/min maximum feed rate) to measure cutting forces. The predicted cutting forces and chip shapes were then compared with experimental results and showed good agreement [24].

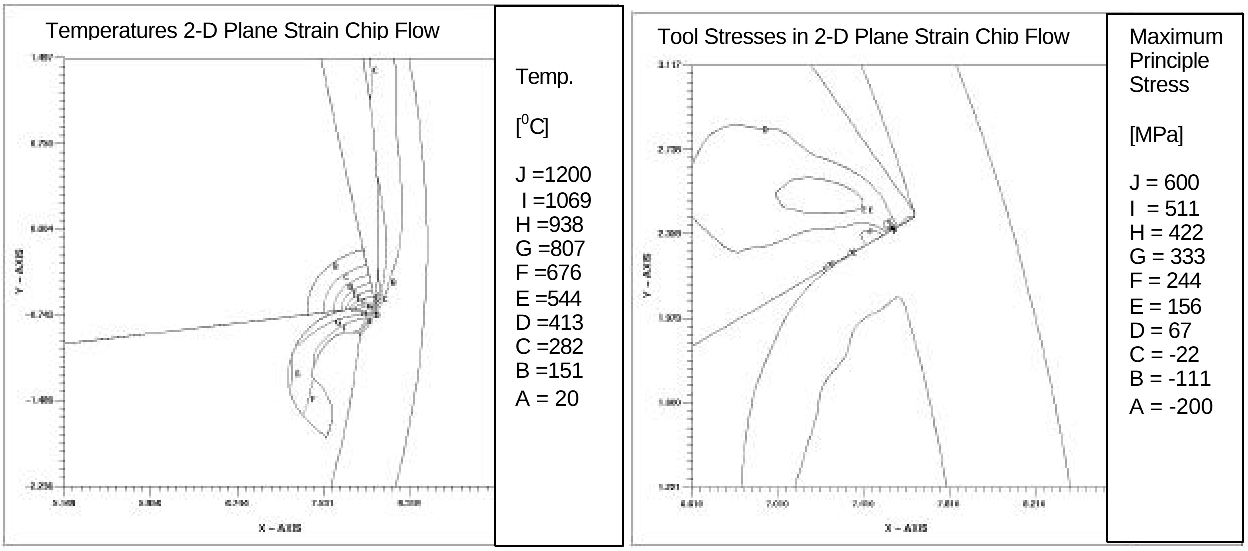


Figure 15: Simulation of 2-D plane strain chip flow in flat end milling when P20 mold steel with uncoated carbide tool (V_c=200 m/min, f_z= 0.100 mm, rake angle=-11.4°, hone radius=0.012 mm) [24]

4.2 Modeling of Chip Flow around Nose Radius in Flat End Milling

The chip flow around the nose radius in flat end milling using a single indexable insert involves axisymmetric workpiece deformation. Thus, by using the same techniques as described above for turning, an axisymmetric deformation model can be used. However, the undeformed chip geometry in this model has variable chip thickness over the rotation of the cutting tool. This process is modeled with 2-D FEM simulation of axisymmetric deformation. Cutting forces, chip flow angle, and distributions of tool temperatures and stresses are also predicted.

5. CONCLUSIONS AND FUTURE WORK

In this study, a methodology was developed and applied to orthogonal machining of P20 mold steel (30 HRC) using uncoated carbide tooling. The friction at the chip-tool contact was estimated by using the flow stress data determined at high speed cutting conditions using experimental data and FEM simulations. Obviously, this method provides a relatively simple approach to estimate the variations of flow stress and friction conditions within the range of high speed machining, with minimum number of experiments. This process model was extended to modeling of turning process using nose radius cutting tools where the cutting process is simulated with plane strain and axisymmetric plastic deformation analysis. The resultant cutting forces, tool stresses and temperatures were predicted in the primary and secondary cutting edges accordingly by using modular deformation regions for turning process. Furthermore, this technique was applied to modeling cutting process in flat end milling using straight cutting edge inserts with nose radius corners. By applying similar deformation models; resultant cutting forces, tool stresses and temperature distribution in flat end milling process can be predicted. The detailed knowledge of predicted temperatures and stresses allows to analyze, predict and optimize process variables that affect: a) tool related characteristics such as tool wear, tool chipping, and tool geometry, b) localized surface layer deformation and residual stresses on the machined workpiece.

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REFERENCES

[1] Tönshoff, H.K., Bussmann, W., and Stanske, C., 1986, Requirements on Tools and Machines when Machining Hard Materials, *Proc. of the 26th Int. Mach. Tool and Res. Conf*. pp.349-357.

[2] Oxley, P.L.B., 1989, Mechanics of Machining, An Analytical Approach to Assessing Machinability. *Halsted Press, John Wiley & Sons Limited*, New York.

[3] Maekawa, K., Shirakashi, T., and Usui, E., 1983, Flow Stress of Low Carbon Steel at High Temperature and Strain Rate (Part 2), *Bull. Japan Soc. Of Prec. Engr.,* Vol. 17, No.3, pp.167-172.

[4] Childs, T.H., Dirikolu, M.H., Sammons, M.D.S., Maekawa, K., and Kitagawa, T., 1997, Experiments on and Finite Element Modeling of Turning Free-Cutting Steels at Cutting Speeds up to 250 m/min, *Proceedings of 1st French and German Conf. On High Speed Mach.,* pp.325-331.

[5] Ernst , H., and Merchant, M.E., 1941, Chip Formation, Friction and High Quality Machined Surfaces, *Trans. Am. Soc. Met.* 29, pp. 299-378.

[6] Lee, E.H., Shaffer, B.W., 1951, The Theory of Plasticity Applied To A Problem of Machining, *Journal of Applied Mechanics,* Vol.18, pp. 405-413.

[7] Altan, T., Kobayashi, S., Ostafiev, V., 1968, Numerical Calculation of The Temperature Distribution in Orthogonal Metal Cutting, *ASME Winter Annual Meeting*-1968.

[8] Tay, A.O., Stevenson, M.G., de Vahl Davis, G., 1974, Using the Finite Element Method to Determine Temperature Distributions in Orthogonal Machining*, Proc. Instn. Mech. Engrs*., 188 , pp 627-638.

[9] Hastings, W.F., and Oxley, P.L.B, 1976, Predicting Tool Life From Fundamental Work Material Properties and Cutting Conditions, *CIRP Annals*, pp. 105-109.

[10] Zorev, N.N., 1963, Inter-Relationship Between Shear Processes Occurring Along Tool Face And Shear Plane In Metal Cutting, *International Research in Production Engineering. ASME*, New York, pp. 42-49.

[11] Usui, E., and Shirakashi, T., 1982, Mechanics of Machining -from Descriptive to Predictive Theory. In On the Art of Cutting Metals-75 years Later, *ASME Publication* PED 7, pp. 13-35.

[12] Strenkowski, J.S., and Carroll, J.T., 1985, A Finite Element Model of Orthogonal Metal Cutting., *ASME J. Engineering for Industry* 107, pp. 346-354.

[13] Iwata, K., Osakada, K., Terasaka, Y., 1984, Process Modeling of Orthogonal Cutting by the Rigid-Plastic Finite Element Method, *Trans. of the ASME, J. of Engineering for Industry*, Vol. 106, pp. 132-138

[14] Shih, A.J., Chandrasekar, S., Yang, H.T., 1990, Finite Element Simulation of Metal Cutting Process with Strain-Rate and Temperatures Effects, *ASME*, PED- Vol. 43, pp. 11-24.

[15] Komvopoulos, K., Erpenbeck, S.A., 1991, Finite Element Modeling of Orthogonal Metal Cutting, *ASME J. Eng. for Ind. Vol. 113*, pp. 253-267.

[16] Marusich, T.D., Ortiz, M., 1995, Modeling and Simulation of High Speed Machining, *International Journal for Numerical Methods in Engineering*, Vol. 38, pp. 3675-3694.

[17] Ueda, K., Watanabe, K., 1993, Rigid-Plastic FEM Analysis of Three-Dimensional Deformation Field in Chip Formation Process, *Annals of the CIRP*, Vol. 42/1/1993

[18] Strenkowski, J.S., and Lin, J.C., 1996, An Analytical Finite Element Model For Predicting Three-Dimensional Tool Forces and Chip Flow, *Manuf. Science and Engr.,* MED-Vol.4, pp. 273-280.

[19] Fang, X.D., and Jawahir, I.S., 1996, An Analytical Model for Cyclic Chip Formation in 2D Machining with Chip Breaking, *Annals of the CIRP*, Vol.15/1/, pp. 53-58.

[20] Shinozuka, J., Obikawa, T., and Shirakashi, T., 1996, Chip Breaking Analysis from the Viewpoint of the Optimum Cutting Tool Geometry Design, *J. Mat. Proc. Tech.* Vol. 62, pp. 345-351.

[21] Armarego, E.J.A., Jawahir, I.S., Ostafiev, V.A., Venuvinod, P.K., 1996, Modeling of Machining Operations-a review of the literature, *the CIRP STC Meeting*, Paris, France.

[22] Ceretti, E., Fallböhmer, P., Wu, W.T., Altan, T., 1996, Application of 2-D FEM to Chip Formation in Orthogonal Cutting*, J. of Materials Processing Tech.*, Vol. 59, pp. 169-181.

[23] Kumar, S., Fallböhmer, P., Altan, T., 1997, Computer Simulation of Orthogonal Metal Cutting Processes: Determination of Material Properties And Effects of Tool Geometry On Chip Flow, *Technical Papers of NAMRI/SME ,* Vol. XXV, pp.177/1-6.

[24] Özel, T., Lucchi, M., Rodriguez, C., and Altan, T., 1998, Prediction of Chip Formation and Cutting Forces in Flat End Milling: Comparison of Process Simulations with Experiments*, Trans. of NAMRI/SME,* Vol. XXVI.

[25] Nakayama, K., 1974, The Formation of Saw Tooth Chips, *Proc. Int. Conf. on Prod. Engr.,* Tokyo, p. 572.

[26] Stephenson, D.A., and Bandyopadhyay, P., 1997, Process-Independent Force Characterization for Metal Cutting Simulation, *ASME J. of Engineering Materials and Technology*, Vol.119, pp. 86-94.

[27] Fu, H.J., DeVor, R.E., Kapoor, S.G., 1984, A mechanistic Model for Prediction of the Force System in Face Milling Operation, *ASME Journal of Engineering for Industry,* Vol. 106, pp. 81-88.

[28] Budak, E., and Altintas, Y., 1993, Prediction of milling force coefficients from orthogonal cutting data, *Manufacturing Science and Engineering ASME PED*, Vol. 64, pp. 453-459.

[29] Shin, Y.C. and Waters, A. J., 1997, A New Procedure to Determine Instantaneous Cutting Force Coefficients for Machining Prediction, *Int. J. Machine Tools Manufacturing*, Vol. 37, pp. 1337-1351.