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Finite Element Modelling In Orthogonal Machining Of Aisi 4340 Using Abaqus Software

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Abstract— **The aim of this paper is to create a simulation model to examine the residual stresses and cutting forces induced by orthogonal machining in the finished work piece by MQL (Minimum Quantity Lubrication) and the model is validated by comparing it with experimental result. The finite element method is used to simulate and analyze the residual stresses induced by an orthogonal metal cutting process. The Johnson-Cook material model is used to describe the work material behaviour and fully coupled thermal- stress analysis are combined to realistically simulate high speed machining with an orthogonal cutting. Finite Element modelling of Residual stresses and resultant surface properties induced by round edge cutting tools is performed as case studies for high speed orthogonal machining of 20NiCrMo5 steel. As a conclusion we can say that results from 2D simulations are very close to the experimental results at the surface level, but there is bit difference when we go down in the material. In 3D simulation, results agree with the experimental values in all levels. Hence we can say that it is possible to model residual stresses, induced by orthogonal machining with accepted amount of accuracy.**

Index Terms— **FEM, ABAQUS, 2D Simulation, 3D Simulation, Johnson Cook Material, Orthogonal Machining**

I. INTRODUCTION

The dictionary definition of mist goes as follows, "A cloud of tiny water droplets suspended in the atmosphere at or near the earth's surface". In simple words, mist particles are the suspended particles of liquid in air. It results due to condensation of air near the earth's surface. In terms of technical analogy, the mixture (or suspension) of the cutting oil particles in air can be called as oil mist. Thus when the soluble cutting fluid is mixed with high pressure (compressed) air and fed at the outlet through a nozzle or venturi, it is possible to generate spray of oil particles coming out at high velocities, in simple terms called as oil mist. Due to its turbulent mixture with air, the oil particles tend to break into smaller globules which readily occupy difficult to reach and rare spots on the interface of work-tool. This type of supply of cutting fluid is another form of supplying heat reducing and lubricating cutting fluid on the work- tool interface, the other method being flood type machining. In the present industrial scenario, it is believed that using the cutting fluid in the form of mist particles or tiny globules of oil particles suspended in air and sprayed at higher velocities, the motion of the cutting fluid at higher rates and denser properties of the mist particles helps to reduce the cutting temperature at the work-tool interface which is essential for the proper machining of hardened high quality materials, providing better dimensional and surface accuracy. These mist particles also tend to occupy larger area correspondingly. The device which supplies mist to the work-tool interface is collectively called as Mist Generator or Mist Supplier. A Mist Generator is a system which pneumatically conveys the droplets of the special oil from central source to the point of application. An oil mist system is economical in its use of lubricant or the cutting fluid and efficient on many types of antifriction applications.

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II. LITERATURE REVIEW

Several studies on residual stresses induced by machining have been performed. Unfortunately, due to limitations in finite element (FE) modelling of the metal cutting process and the complex physical phenomenon involving the formation of machining residual stresses, most of these studies remain experimental in nature [1,2,3,4].
Although many studies on FE modelling of the orthogonal cutting process have been published until now, these were mainly applied to predict with reasonable accuracy of the strains, stress and temperatures during cutting [5, 6, 7, 8, 9, 10]. Only a few studies on FE modelling involving the prediction of the machining residual stresses with decent accuracy can be found in the literature, with special attention to the residual stresses in plain carbon steels and hardened steels [11,12].Concerning modelling of machining induced residual stresses in stainless steels, the available studies are even more restricted [7,8,9].Wiesner [10] studied the residual stresses generated after orthogonal cutting of AISI 304 steel using uncoated cemented carbide tools. Using the X-ray diffraction technique, Wiesner determined the influence of the cutting speed and cutting depth on in-depth distribution of the residual stresses in the direction of primary motion (the cutting speed direction). High tensile residual stresses (close to +700MPa) were found on the machined surface. In order to explain these high tensile residual stresses, a finite element method (FEM) was employed to analyse the influence of the thermal and mechanical effects on the residual stress state separately, although in the paper he presents the results for the thermal effect only. Wiesner concluded that the thermal effect is not the only reason for tensile residual stresses in machined components. The mechanical effect does not always produce compressive residual stresses, but can also contribute to tensile residual stresses.

Liu and Guo [13] proposed an FE model to investigate the effect of sequential cuts and tool-chip friction on residual stresses in a machined layer of AISI 304 steel. They reported a reduction in the superficial residual stresses when the second cut is performed. Moreover, the residual stresses can be compressive, depending on the uncut chip thickness of the second cut. They also found that residual stress on the machined surface is very sensitive to the friction condition of the tool–chip interface. Later, using the same work material, Liu and Guo [14] presented a similar study on the effect of sequential cuts on residual stresses. They showed that decreasing the uncut chip thickness below a critical value in the second cut may result in favorable compressive residual stress distribution. Thus, they conclude that it would be better to set an appropriate finishing cut condition in consideration of the effects of sequential cuts to control the residual stress distribution. Unfortunately, Liu and Guo[14] did not present any experimental evidence for the work material under investigation (AISI 304 steel) to validate their FE model.

Yang and Liu [15] performed a sensitivity study of the friction condition on the tool–chip contact, the cutting forces and the residual stresses in machining-affected layers of AISI 304 steel. In this study they proposed a new stress based polynomial model for modelling the tool–chip contact, which represents a simple curve fitting the experimentally obtained shear and normal stresses acting at the tool–chip interface. When comparing this new friction model with other friction models based on an average friction coefficient deduced from cutting forces or from stresses, they found significant differences among the predicted residual stresses. They concluded that the conventional force-based friction model is inadequate to predict the residual stresses induced by machining, and they showed the potential for improving the quality in predicting machining residual stress by adopting the stress based polynomial model. Although it is widely accepted that friction conditions will change along the tool–chip contact length, the authors did not present any experimental evidence to support their conclusions.

The prior investigations show that modelling residual stress in machining stainless steel was studied for a very limited range of cutting conditions and for specific analysis. Özel and Zeren [16, 17] propose a model to simulate the effect of cutting edge radius on the induced stresses and Özel and Altan [18] also work in this area to simulated the flow of stress in the machined work piece and find the effect of tool-chip friction on the stress field, but they have simulated model with pre-define chip geometry to get the continuous chip formation using ALE adaptive meshing techniques which seems not very realistic.

Most of the FE-modelling have been performed with 2D models [7,15,16,17,18] & [5, 6, 7, 8, 9, 10] due to complexity of 3D model, where we need consider the translational motion of tool and the rotation motion of the workpiece for the orthogonal machining. These two mutually perpendicular motions make the numerical model very complex to simulate for the researcher. But M. Vaz Jr. et.al [19], Özel and Zeren [7, 16] have presented FE-models for the 3D case in their studies. Unfortunately they only considered the one dimensional motion of either tool or workpiece in their proposed 3D models of orthogonal machining simulation, which makes their models 3D turning operation instead of 3D orthogonal machining .Also it keep the model bit apart from the reality of orthogonal machining.

III. OBJECTIVE

To study and compare the heat generated and stress induced during orthogonal machining by minimum quantity lubrication (MQL) using Mac Sherol B lubrication. The study, analysis and modeling are done using ABAQUS software.

IV. MATERIAL DESCRIPTION: AISI 4340 STEEL

4.1 Chemical Composition

Table -1: Chemical Composition of AISI 4340 Steel

Carbon	0.38 - 0.43%
Chromium	0.7 - 0.9%
Manganese	0.6 - 0.8%
Nickel	1.65 – 2%
Molybdenum	0.2 - 0.3%
Phosphorus	0.035% max
Silicon	0.15 - 0.3%
Sulphur	0.04% max
Iron	Balance

4.2 Physical Properties

Table -2: Physical Properties of AISI 4340 Steel

Density (kg/m^3)	7700-8030
Specific Gravity	7.8
Specific Heat (Btu/lb/^{0}F – [32-212 ^{0}F]	0.116
Melting Point (^{0}F)	2600
Thermal Conductivity(W/m K)	21
Mean Coeff. Thermal Expansion / ^{o}C	11.5 x 10^{-6}
Modulus of Elasticity Tension (GPa)	190-210
Hardness Rockwell (HRC)	35

4.3 Typical Applications

Typical applications include structural use, such as aircraft landing gear, power transmission gears and shafts and other structural parts. Some other application include Heavy-duty axles, shafts, heavy-duty Gears, spindles, pins, studs, collets, bolts, couplings, sprockets, pinions, Torsion bars, connecting rods, crow bars, conveyor parts etc.

All these applications include proper surface finishing after machining, otherwise the ultimate structure may collapse due to presence of residual stresses induced due to micro cracks on surface and sub-surface when put into application. As a result, the objective of reducing the overall cutting temperature on the work-tool interface is done on AISI 4340 Steel by applying oil-mist cooling. It is aimed that when AISI 4340 steel is machined with mist application of coolant oil, the residual stresses on the surface reduce to a very large extent as the cutting temperature reduces at a very large rate. This ensures typical justification of mist machining for real time applications.

V. MATERIAL AND MODEL

5.1 Constitutive Material Model

In FEA, accurate flow stress models are considered highly necessary to represent work material constitutive behaviour under high strain-rate deformation conditions In this model, the constant A is the initial yield strength of the material at room temperature and a strain rate of 1/s and s¯ represents the plastic equivalent strain. The strain is normalized with a reference strain rate s and s_0. Temperature term in the J-C model reduces the flow stress to zero at the melting temperature of the work material, leaving the constitutive model with no temperature of the work material, leaving the constitutive model with no temperature of the work material, leaving the constitutive model with no temperature effect. In this study, FEA of machining of 20NiCrMo5 steel in annealed condition is investigated and its J-C material model constants are given in Table 4.1.The J-C material model constants used for this simulation are experimentally determined in SWEREA KIMAB lab by Dr. Chandrashekharan.

5.2 Tool Chip Friction Model

Friction along the tool–chip contact interface, during the cutting process, is a very complex phenomenon [5, 7, 8, 14, 15 and 17]. It influences the chip geometry, built-up edge formation, cutting temperature and tool wear. Therefore, it is necessary to understand the friction mechanism across the faces and around the edge of the tool, in order to be able to develop accurate models for cutting forces and temperature. The most simple friction model is Coulomb friction given by

$\tau = \mu\sigma$

where, τ is the frictional shear stress and σ is the normal stress to the surface. Usually the friction coefficient μ is assumed to be constant for a given interface [8]. There exist advanced models that are more relevant for the cutting process where rate, pressure and temperature dependency are accounted for. However, it is not possible to perform direct measurements of these for the extreme conditions that exist in the contact region. Therefore Modified Coulomb Friction Law is adopted to model the effect of contact friction along the tool-chip interface, it states that relative motion at a contact point will occur if the applied shear stress τ tangent to the contact interface reaches the critical frictional shear stress τ_c defined below equation

$\tau c = \min(\mu_p, \tau_{th})$

where, p is the normal pressure at the contact point, μ is the coefficient of friction, and τth is a threshold shear stress value. It is noted that, when τ_{th} is set to infinity, the conventional Coulomb Friction Law is recovered. In this study, the work piece material is 20NiCrMo5 steel and τ_{th} is taken to be 210 MPa, which is equal to the material's yield stress in simple shear.

5.3 Contact Pair Modeling

Contact modelling is of great importance in metal machining due to the important effects associated with the tool–chip interface. The two most common algorithms for solving contact problems are the penalty approach and Kinematic approach. In this study Kinematic predictor/corrector Contact Algorithm [22] is used for the contact between tool and work material with high stiffness value of 210MPa.These special procedures have been developed for the explicit integration method, such as momentum- related techniques in which modifications are made to the acceleration, velocities and displacements. One of the aims of the latter is to avoid the penalizing effect on the time step of the explicit procedure, which can be introduced by the high stiffness, associated with penalty approaches. The contact condition is not fulfilled exactly in the penalty approach. Kinematic predictor/corrector Contact Algorithm [22] method has used by Özel and Zeren [7,16,17] in their study of FE Modelling of high speed marching.

VI. SIMULATION, RESULT AND DISCUSSION

FEM simulation has been conducted under the orthogonal machining condition, by utilizing the proposed ALE with pure Lagrangian boundaries scheme.

6.1 Residual Stress

The machining operation generates large amounts of residual stress, called induced residual stress in the surface layer of the finished work piece component. These unwanted stresses are totally governed by the different cutting parameter during machining process. The residual stress on the machined surface is an important factor in determining the performance and fatigue strength of the work piece. Therefore, it is important to understand and control the residual stress state in the machined part so that undesired failure can be avoided.

In the past few years this has been a very interesting research issue A combined numerical/experimental study of the behavior of different cutting parameters on cutting forces and residual stresses was undertaken by many of the researchers, Kalhori (2001) [8] ,C.Shet and X.Deng (2002) [9],Özel and Zeren(1998) [16]. But all the studies not focusing on the same approaches ´, they differ by lot of different aspect of orthogonal machining and judging the resulting parameters. These studies used ALE-algorithm with predefined chip geometry to simulate the machining operation but this study the concept of predefined chip geometry has been dropped to simulate the model in a more realistic way. Measurements in the cutting zone are particularly difficult to perform due to the hostile environment. Several laboratory experiments were performed in order to simulate different cutting conditions frequently encountered in practice. As evidence of the ability of the simulation procedure to model residual stresses in machined parts, a comparison is made between finite element predictions in this study and experimental results available in the literature. In the finite element simulation, the work piece is made of 20NiCrMo5 steel and has an in plane dimension of 5 mm by 2 mm. The tool rake angle is 6°, the velocity of cutting is 260 m/min, and the different depth of cut is 0.2 mm, 0.4mm, 0.8mm. A mesh containing 41740 nodes and 41503 linear quadrilateral elements of type CPE4RT plane strain elements is used. The simulation the steady state was first reached after a cut of only 2–3 mm. To make sure a full steady state is developed, the simulation is continued until a cut of 4–5 mm is completed. To collect the data from simulation, residual stresses value in axial(zz) and circumferential (xx) measured at three different points(P-1,P-2,P-3) along the depth from the surface a up to 210µm.further the three measured values are averaged. The main reason to adopt this measurement technique is to co- relate the simulation measurement with experimental measurement. During experimental measurements residual stress values are collected by averaging the measured values at three points for three different cases. Also residual stress measured at the integration point along the path at steady state. The whole scheme is given in the Figures.

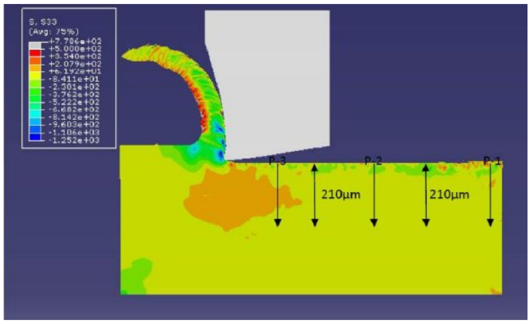

Fig -1: Simulated residual stress in axial direction for the depth of cut 0.2mm after steady state condition

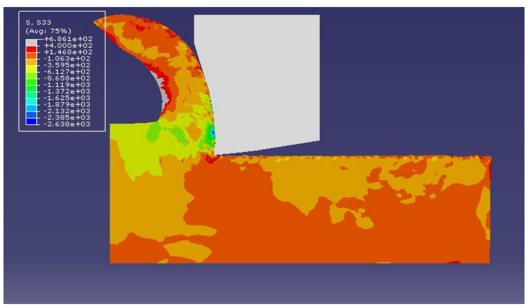

Fig -2: Simulated residual stress in axial direction for the depth of cut 0.4mm after steady state condition

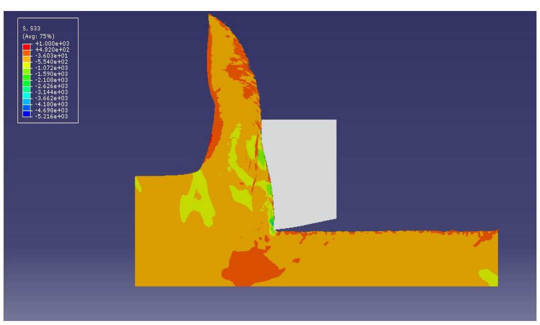

Fig -3: Simulated residual stress in axial direction for the depth of cut 0.8mm after steady state condition

6.2 Circumferential Stress (S_{zz})

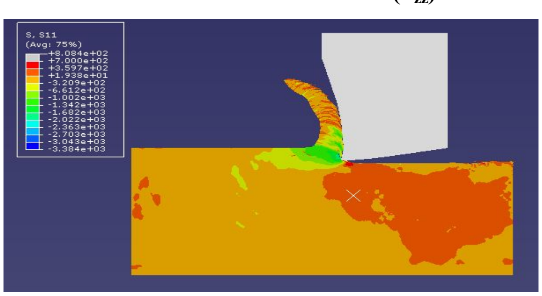

Fig -4: Simulated residual stress in circumferential direction for the depth of cut 0.2mm

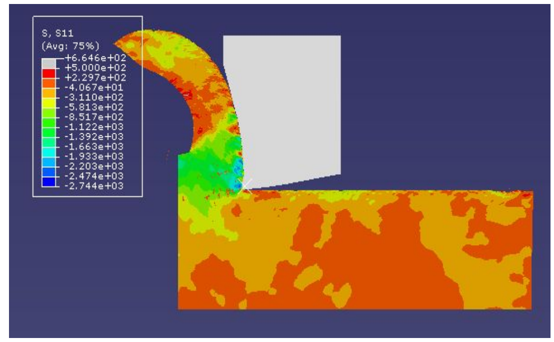

Fig -5: Simulated residual stress in circumferential direction for the depth of cut 0.4mm

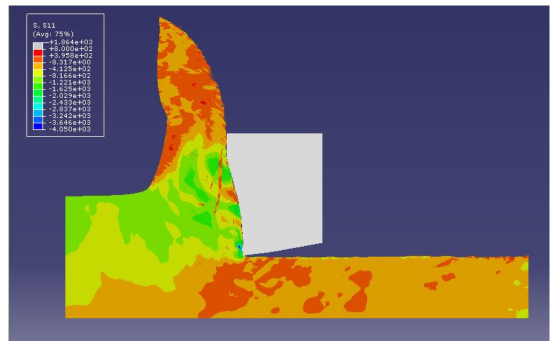

Fig -6: Simulated residual stress in circumferential direction for the depth of cut 0.8mm

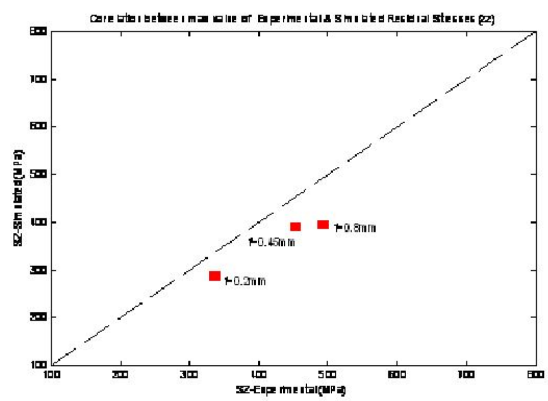

Fig -7: Correlation between Experimental and simulated value of max S(zz) at different ‘f’

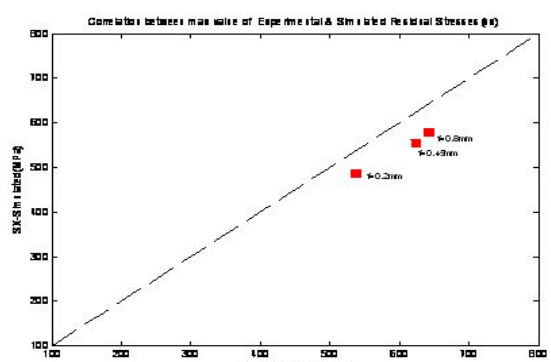

Fig -8: Correlation between Experimental and simulated value of max S(xx) at different ‘f’

Table -3: % error in measured and simulated max-value S(zz) & S(xx) at different depth of cut(f)

Depth of cut (f) in mm	**% error for S(zz) axial**	**% error for S(xx) circumferential**
0.2 mm	14.4214	9.4796
0.4 mm	19.4908	10.8974
0.8 mm	13.3893	10.3421

VII. FUTURE SCOPE

The future scope is to investigate the efficiency of mist machining of strong and difficult of machine materials like Titanium (64) Alloy and Inconel Alloys and compare the effectiveness over dry and wet machining. Similar factors are to be considered and Carbide inserts with PVD coatings are to be used.

The immediate future objective is to measure the flank wear using Metallurgical microscope fitted with micrometer. Also, the cutting inserts will be inspected under scanning electron microscope (SEM) to study the prevalent wear mechanism. Finally, a finite element model for dry and wet machining will be developed and compared with the experimental results of mist machining.

CONCLUSION

In this research, the explicit dynamic Arbitrary Lagrangian, Eulerian (ALE) method with adaptive meshing capability has been used to develop FEM simulation model. The Commercial finite element code Abaqus/ExplicitV6.8 is used for modeling for orthogonal cutting of 20NiCrMo5 steel using round edge carbide cutting tools. No remeshing scheme is employed in the model. The extended Johnson-Cook work material model and a detailed friction model are also employed and work material flow around the round edge of the cutting tool is simulated in conjunction with an adaptive meshing scheme.

The Prediction of the machining induced residual stresses in the Axial and Tangential direction is the main focus point of this research and it's effectively carried out, afterwards the predicted values are compared with the experimental values in the table-6, to validate the model. The development of temperature fields during the cutting process, Forces on the tool, strain rate in primary shear zone, shear angle changes and the chip thickness for the different cutting depth is also captured.

Also the effects of changing of different cutting parameters on residual stresses are studied in this work. Process induced stress profiles depict that there exist both compressive and tensile stress regions beneath the surface. Finite Element modeling of stresses and resultant surface properties induced by round edge cutting tools is performed for high speed machining of 20NiCrMo5 steel for different depth of cuts. The results indicate that the round edge design tools influence the stress and temperature fields greatly.

These predictions combined with the temperature field predictions are highly essential to further predict surface integrity and thermo-mechanical deformation related property alteration on the microstructure of the machined surfaces. It has been demonstrated that the ALE simulation approach presented in this work without remeshing definitely results the better predictions for machining induced stresses.

As a remark I would like to say Numerical simulation of machining has proved to be a challenge to existing algorithms and computational tools. Large and localized plastic deformation and complex contact condition are some of the difficulties associated with this class of problems. The intent of this research is to illustrate different approaches used and the advancements in this field. In spite of the current progress, there is still a need for more research before a modeling practice is established that can predict residual stresses with an acceptable degree of accuracy. The modeling of the material behavior and friction in the process zone is particularly uncertain.

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REFERENCES

[1] Shih, A. J., 1995, "Finite element simulation of orthogonal metal cutting," ASME Journal of Engineering for Industry, 117, 84-93.
[2] Strenkowski, J.S. and Carroll, J.T., 1985, "A finite element model of orthogonal Metal cutting," ASME Journal of Engineering for Industry, 107, 346-354.
[3] Strenkowski, J.S. and Carroll, J.T., 1986, "Finite element models of orthogonal cutting with application to single point diamond turning," Int. Journal of Mechanical Science, 30, 899-920.
[4] Black, J. T. and Huang, J. M., 1996, "An evaluation of chip separation criteria for the fem simulation of machining", ASME Journal of Manufacturing Science and Engineering, 118, 545 – 553.
[5] Madhavan, V., Chandrasekar, S. and Farris, T.N., 2000, "Machining as a wedge indentation," Journal of Applied Mechanics, 67, 128-139
[6] Olovsson, L., Nilsson, L., and Simonsson, K., 1999, ''an ALE Formulation for the Solution of Two-Dimensional Metal Cutting Problems,'' Computers and Structures, 72, 497–507.
[7] Özel, T. and Zeren, E., 2005, "Finite Element Modeling of Stresses Induced by HighSpeed Machining with Round Edge Cutting Tools," Proc. of IMECE'05, Paper No. 81046, November 5-11, 2005, Orlando, Florida, USA.
[8] M. Vaz Jr. • D.R.J. Owen ,V. Kalhori • M. Lundblad • L.-E. Lindgren, Modelling and Simulation of Machining Processes.
[9] C.Shet, X.Deng , Residual stresses and strains in orthogonal metal cutting, International Journal of Machine Tools & Manufacture 43 (2003) 573–587.
[10] C Wisner Residual stresses after orthogonal machining of AlSl 304: numerical calculation of the thermal component and comparison with experimental results Journal Metallurgical and Materials Transactions A (2007) 989-996
[11] Marusich, T.D. and Ortiz, M., 1995, "Modeling and simulation of high- speed machining," Int. Journal for Numerical Methods in Engineering, 38, 3675- 3694.
[12] Ceretti, E., Fallböhmer, P., Wu, W.T. and Altan, T., 1996, "Application of 2-D FEM to chip formation in orthogonal cutting," Journal of Materials Processing Technology, 59, 169-181.
[13] Liu and Guo Finite element modeling the influence of edge roundness on the stress and temperature fields induced by high-speed machining, The International Journal of Advanced Manufacturing Technology March (2006) 255-267