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Finite Element based Simulation of Orthogonal Cutting Process to Determine Residual Stress Induced

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ABSTRACT

The essence of this research work is to develop a finite element based simulation model of orthogonal cutting process and determine residual stress induced in component. Thermo-mechanical forces generated at tool-chip interface are responsible for metal cutting operation. These forces are induced on surface or sub-surface layer of work piece and tool in the form of residual stress. Experimentally it is quite difficult to get the values of forces and residual stress. Residual stress has considerable effect on life of a component when subjected to fatigue or variable loading. In real time almost all components are machined to get required surface finish and dimensional accuracy. Hence, knowledge about machining induced residual stress magnitude and its direction will be of great use while designing the component. This can improve life of component and chances of sudden or accidental failure of critical machine parts can be minimized. The current research work is focused on, finite element simulation of orthogonal machining process on different materials and to get magnitude and direction of residual stress induced in work-piece as result of simulation model. To describe work material behavior Johnson-cook material model is used. A fully coupled Thermo-mechanical analysis is developed to realistically simulate the machining process. As a conclusion graphical analysis of residual stress vs machining parameters will be done, from which decision about selection of optimum machining process, to improve component life can be made.

Keywords

FE-modeling, ALE formulation, ABAQUS, Machining, Simulation, Residual stress

1. INTRODUCTION

The accurate and reliable flow stress models are considered to represent work material constitutive behavior under high-speed cutting conditions especially for a material. The consistency of structural components obtained by machining operations is influenced by the state of residual stresses induced in the component as a result of various manufacturing processes[2]. The residual stress is remains inside the component when there is no external load. This can be tensile or compressive in nature. According to research literature, having tensile residual stress in the region of the machined surface has negative effects on fatigue, fracture resistance, stress corrosion and can substantially reduce the component life. In order to improve the product quality, its sustainability under fluctuating load and tool life, a better understanding of manufacturing process chain used and the residual stress induced in the finished part is required. To get the required shape, size and surface finish almost all components are been machined. Usually the machining is done at last to achieve the required dimensional accuracy. As stated above machining induced residual stress has direct impact on life of component. Hence, primary objective of this work is to investigate the residual stress generated during machining process. Most of the researchers have made successful efforts to determine various forces generated during machining process and their influence on tool and the workpiece[4]. The experimental techniques suggested, are tedious, time consuming and costly. Some of the researchers use an analytical approach, but due to high complexity of process parameters these are based on certain assumptions. An attempt is also made to simulate the machining process by using finite element method. The result of the finite based simulation shows closer agreement with the experimental value. Still the research work is lagging in this direction as far as generalization of model and selection of optimum process parameters for particular material is concerned. Due to high complexity involved while simulating machining process using FE codes, the proposed work is limited to simulation of orthogonal metal cutting process using commercial finite element code. In this research work, the basic orthogonal machining process will be simulated using commercial finite element code which will give magnitude and directions of various forces on tool and the workpiece and most important, magnitude of residual stress induced in the workpiece and its direction. To make the model more generalized, simulation will be done by varying the orthogonal machining process parameters such as speed, feed, depth of cut, tool geometry and workpiece material. Further transient thermal analysis to simulate high temperature generated and induced, on tool and the workpiece due to tool chip interaction. The comparative study of machining process parameters, workpiece material and result output obtained from FE simulations for residual stress will be made. Hence, the effect of machining parameter selected on magnitude and direction of residual stresses induced in the workpiece, which will have considerable effect on component life under cyclic loading is investigated.

2. LITERATURE RIVIEW

Several studies on residual stresses induced by machining have been performed. Due to limitation in finite element (FE) modeling 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. In machining process, quite often, process parameters selection is done considering past experience and experimental tests. This approach can lead to high costs and, even worse not necessarily to the best solution. Despite some limitations difficulties in identifying entry parameters, lack of robustness in quantitative results and so on, Finite Element Modeling of chip formation process can be considered as a promising approach to study the cutting process, allowing to reduce the experimental cost. It provides information on some difficult to measure variables like temperature, energy or stress and thus, it contributes to improve general understanding of chip formation process [3,4,5,6] .

According to M. H. Miguélez et al. [2], The reliability of structural components obtained by machining operations is influenced by the state of residual stresses resulting from processing. Having tensile residual stresses in the vicinity of the machined surface has negative effects on fatigue and fracture resistance, on stress corrosion and can substantially reduce the component life. Therefore, the analysis of the residual stresses due to machining operations has been an active subject of research. However, machining is a complex process where large strains and strain-rates are produced and where large temperatures are generated by dissipation of the plastic work and by frictional heating. The complexity of the physics of chip formation and the variety of boundary conditions (the chip has a free surface while also sustaining sticking and frictional sliding along the tool rake face; the workpiece is in contact with the tool at the clearance surface) lead to difficulties in analyzing the generation of residual stresses by pure analytical methods, although some authors have used this approach to predict residual stresses after machining.

Liu and Guo [20] proposed an FE model to investigate the effect of sequential cut and tool-chip friction on residual stresses in a machined layer of AISI304steel. 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 thichness 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 [21] 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 effect of sequential cuts to control the residual stress distribution.

3. WORK MATERIAL MODELLING

2D numerical model is designed and developed with workpiece material ideal plastic AISI 316L steel and elastic tool of same grade. The Johnson Cook constitutive model is taken for workpiece to describes the flow stress of a material with the product of strain, strain rate and temperature effects. The initial cutting speed (V_c) will be 130m/min and feed (F) will be 0.05mm. The Model is as shown in Figure1. The objective is to predict the in-depth residual stress profiles in the machined component for several cutting parameters including: cutting speed, tool geometry, cutting feed and cutting depth. This allows the effect of such cutting parameters in the surface and sub-surface residual stress distributions will be investigated. The Boundary conditions is applied for the both workpiece and tool. The workpiece is fixed in x- direction as well as y-direction. The tool is moving in the x-direction with the prescribed velocity and fixed in y-direction. The finite element modeling will be done by using ABAQUS/ v6.10 software. Abaqus is divided into modules and analysis. The modules include defining the geometry, defining material properties and generating a mesh.

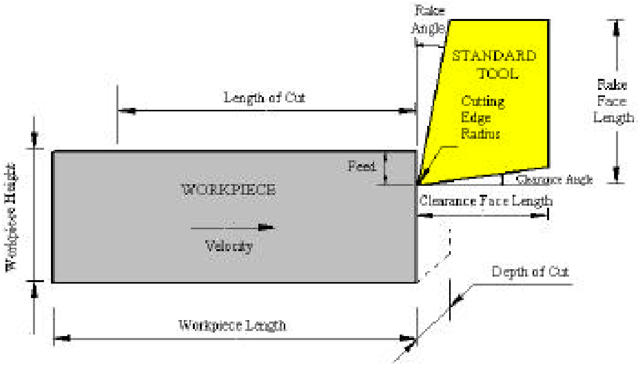


Fig 1: Schematic of orthogonal cutting condition

When the model is completed, Abaqus/CAE generates an input file that will submit to the Abaqus analysis product. Then it generates output database and desired output will be introduced. The adaptive meshing refer is Arbitrary Lagrangian-Eulerian (ALE) analysis. The adaptive meshing technique in ABAQUS combines the features of pure Lagrangian analysis and pure Eulerian analysis. In Lagrangian, nodes move exactly with material points. It is easy to track free surfaces and to apply boundary conditions. The mesh will become distorted with high strain gradients. In Eulerian, nodes stay fixed while material flows through the mesh. It is more difficult to track free surfaces. No mesh distortion because mesh is fixed. The implementation current of Eulerian description is limited. ALE Mesh motion is constrained to the material motion only where necessary (at free boundaries), but otherwise material motion and mesh motion are independent. ALE adaptive meshing is a tool that makes it possible to maintain a high-quality mesh throughout an analysis, even when large deformation or loss of material occurs, by allowing the mesh to move independently of the material. In Abaqus software ALE adaptive meshing can be used to analyze Lagrangian and Eulerian problems (in which material flows through the mesh). It can be used as a continuous adaptive meshing tool for transient analysis problems undergoing large deformations (such as dynamic impact, penetration, and forging problems).

4. RESIDUAL STRESSES

Residual stresses are stresses that remain in a solid material after the original cause of the stresses has been removed. It is well known that machining processes such as turning, milling and drilling, create undesirable tensile residual stresses on the surface of workpiece leading to a reduction in the fatigue life of parts. Residual stresses raise the need for over-tolerant specifications on the parts or require post-processing in order to remove tensile residual stresses. It is very critical to find a fast and precise solution to predict residual stresses in a machined component given the process parameters and material properties. Having a reliable simulation tool for residual stresses allows production engineers to select appropriate cutting conditions in advance. This facilitates the elimination of residual stresses or even altering the state of residual stresses to increase fatigue life using optimum machining conditions. Different approaches to the determination of residual stresses can be summarized as experimental measurements, finite element calculations and analytical models. Although it serves as the ultimate validation tool for numerical or analytical simulations, experimental approach is too costly to be utilized in every scenario. On the other hand, finite element modeling serves as a good simulation tool; however, it is too time-consuming even with state of the art computational resources. And finally, analytical modeling provides a fast alternative [1]. A finite element-based machining model can be employed to determine the effects of cutting process parameters such as cutting speed, tool geometry, cutting feed and chip load on the induced state of residual stress. Typical approaches for numerical modeling of metal cutting are Lagrangian and Eulerian techniques. Lagrangian techniques, the tracking of discrete material points, have been applied to metal cutting for more than two decades. Techniques typically used a predetermined line of separation at the tool tip, propagating a fictitious crack ahead the tool. This method prevents the resolution of the cutting edge radius and accurate resolution of the secondary shear zone due to severe mesh distortion. To alleviate element distortions, others used adaptive re-meshing techniques to resolve the cutting edge radius. Eulerian approaches, tracking volumes rather than material particles, did not have the burden of rezoning distorted meshes. A Lagrangian finite element-based machining model is applied to orthogonal cutting of different materials. Techniques such as adaptive re-meshing, explicit dynamics and tightly couple transient thermal analysis are integrated to model the complex interactions of a cutting tool and workpiece [5].

5. JOHNSON-COOK CONSTITUTIVE 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:

$$\bar{\sigma} = [A + B(\bar{\varepsilon})^n]\left[1 + C\ln\left(\frac{\alpha}{\beta}\right)\right]\left[1 - \frac{T - T_{ROOM}}{T_{MET} - T_{ROOM}}\right] \qquad (1)$$

Where $\bar{\sigma}$ is the equivalent stress, A is in fact the initial yield strength (MPa) of the material at room temperature, B is the hardening modulus, n is the work hardening exponent, C is the coefficient dependent on the strain rate, m is the thermal softening coefficient and a strain rate of 1/s and $\bar{\varepsilon}$represents the equivalent plastic strain. The strain rate α is normalized with a reference strain rate β = $1.0S^{-1}$

T_{room} and T_{melt} represent the room temperature and melting temperature, respectively.

Damage model proposed by Johnson and Cook is used in conjunction with J-C yield model. According to classical damage law, damage (fracture) of an element is defined by

$$D = \sum \frac{\Delta\overline{\in}}{\overline{\in}^f} \qquad (2)$$

Where$\Delta\overline{\in}$is the increment of equivalent plastic strain during an integration step, and $\overline{\in}^f$ is the equivalent strain to fracture, under current conditions. Fracture is then allowed to occur when D=1.0 and the concerned element are removed from computation. According to J-C damage law, the general expressionfor the fracture strain is given by

$$\overline{\in}^f = \left(D_1 + D_2 exp D_3 \frac{\sigma_m}{\bar{\sigma}}\right)\left(1 + D_4 \ln\frac{\alpha}{\beta}\right)\left[1 - D_5\left(1 - \frac{T - T_{ROOM}}{T_{MET} - T_{ROOM}}\right)\right] \qquad (3)$$

Where σ_m is the average of the three normal stresses and $\bar{\sigma}$ is the von Mises equivalent stress. The J-C damage model is suitable for high strain rate deformation, such as high speed machining, therefore, it is most applicable to truly dynamic simulations. 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, values as shown in TABLE I. T is instantaneous temperature, Tr is room temperature and Tm is melting temperature of a given material.

Table 1. Constant of J-C constitutive model

A (MPa)	**B (MPa)**	**n**	**m**	**C**
490	600	0.21	0.6	0.015
D_1	**D_2**	**D_3**	**D_4**	**D_5**
0.05	3.44	2.12	0.002	0.61

6. ALE FORMULATION

In order to understand ALE formulation we need to understand lagrangian formulation and eulerian formulation first.

6.1 Lagrangian Formulation

Lagrangian formulation is mainly used in solid mechanics problems. Here the FE mesh is attached to work piece material and cover the whole of the region under analysis. This makes it highly preferable when unconstrained flow of material is involved. Lagrangian formulation is broadly used in metal cutting simulation due to ability to determine geometry of the chip from incipient stage to steady state and this geometry is a function of cutting parameters, plastic deformation process and material properties. Besides, chip separation criteria can be defined to simulate discontinuous chips or material fracture in metal cutting models which are based on Lagrangian formulation.

Although there are many advantages of Lagrangian formulation, it has a number of short comings. Metal being cut is exposed severe plastic deformation and it causes distortion of the elements. Therefore, mesh regeneration is needed. Secondly, chip separation criteria must be provided. This drawback of formulation can be eliminated by using an updated Lagrangian formulation with mesh adaptivity or automatic remeshing technique.

6.2 Eulerian Formulation

In Eulerian formulation, the FE mesh is spatially fixed and the material flow through the control volume which eliminates element distortion during process. Besides, it requires fewer elements for the analysis, thereby reducing the computation time. Cutting is simulated from the steady state and therefore there is no need for separation criteria in Eulerian based models. The drawback of Eulerian formulation is a need in determining the boundaries and the shape of the chip prior to the simulation. Also the chip thickness, the tool-chip contact length and the contact conditions between tool-chip must be kept constant during analysis which makes Eulerian formulation does not correspond to the real deformation process during metal cutting.

6.3 Arbitrary Lagrangian–Eulerian Formulation (ALE)

In an attempt to combine advantages of both Lagrangian and Eulerian Formulations, a mixed approach, known as Arbitrary Lagrangian–Eulerian formulation (ALE) has been proposed to model machining operations. The best features of Lagrangian and Eulerian formulations have been combined. In ALE formulation, the FE mesh is neither fixed spatially nor attached to the work piece material. The mesh follows the material flow and problem is solved for displacements in Lagrangian step, while the mesh is repositioned and problem is solved for velocities in Eulerian step. The idea used in metal cutting simulation is to utilize Eulerian approach for modeling the area around the tool tip where cutting process occurs. Therefore, severe element distortion is avoided without using remeshing. Lagrangian approach is utilized for the unconstrained flow of material at free boundaries. Furthermore shape of the chip occurs as a function of plastic deformation of the material. This approach is shown in Figure 2.

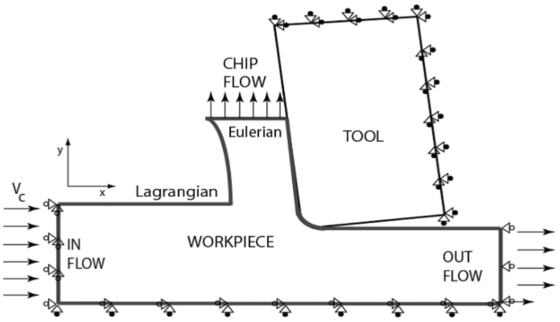


Fig 2: Eulerian and Lagrangian boundary conditions in ALE simulation

7. RESULT AND DISCUSSIONS

Finite element model is developed for simulation of orthogonal machining process. Aluminium and steel 316L are used as work-piece materials. Series of simulations are performed by varying depth of cut. Continuous chip formation is achieved by adjusting flow stress and damage parameters. Figure 3 shows simulation output and colour contour plot of stress distribution over workpiece surface. Residual stress is that, which remains in material after removal of external load. In order to capture the values of residual stresses induced over workpiece surface - sub surface layers, probe values are measured at different node layers after equilibrium is achieved. The measurement technique used is as shown in figure 4. It is assumed that equilibrium is achieved when stress flow pattern becomes steady or when tool reaches the extreme position. Graphs of residual stress vs. depth beneath the surface are plotted.

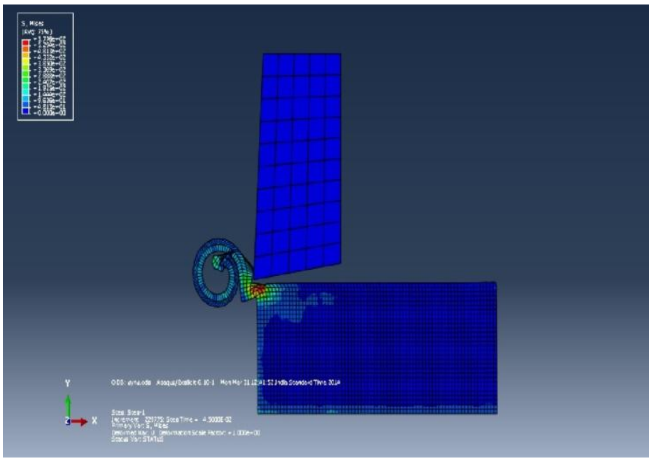


Fig 3: Simulation result for AISI 316 L steel

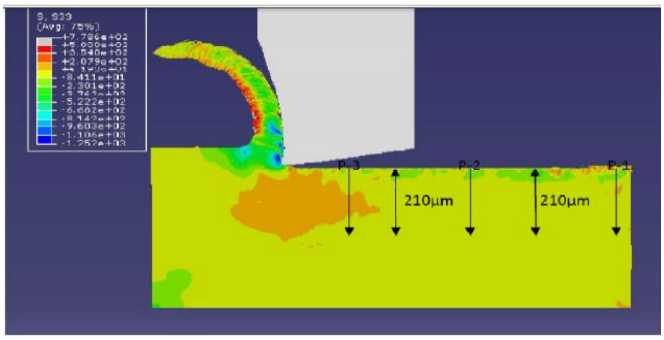
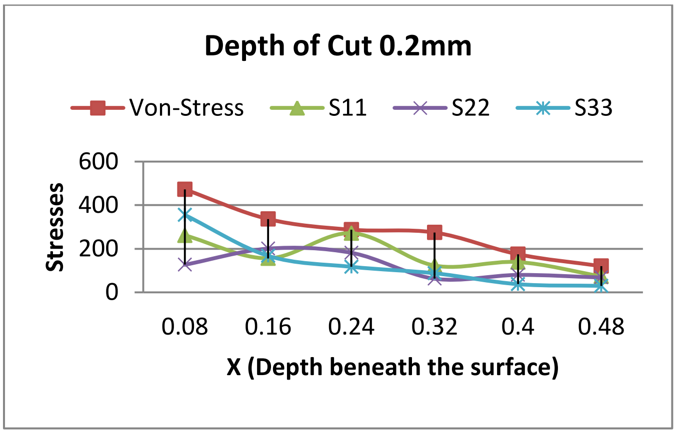
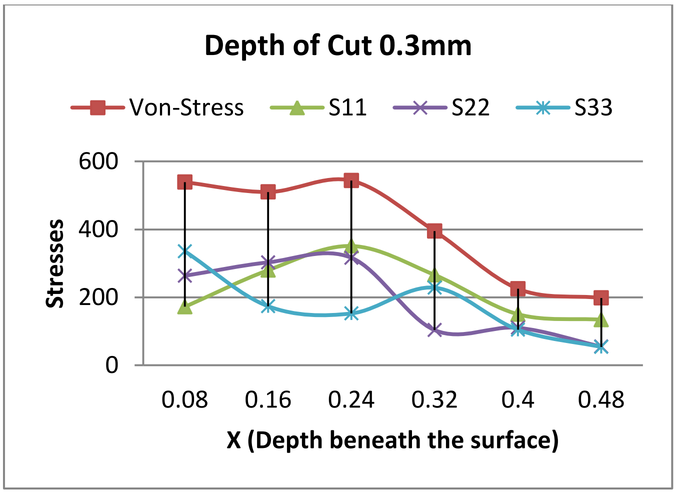


Fig 4: Measurement technique for residual stress

Results of residual stress patterns obtained for STEEL316L are shown in figure 5. From the graphical behavior it can be stated that residual stresses are maximum at top surface layers and decreases gradually as we move to sub surface layers beneath the finish work piece. Also slight change in maximum residual stress is noticed as the depth of cut varies from 0.2mm - 0.4mm. The maximum resultant residual stress for 0.2mm, 0.3mm, 0.4mm depth of cut are 475MPa, 550MPa, 450MPa respectively.

The obtained results are compared with real time experimental data extrapolated from research literatures. Residual stress pattern for STEEL316L when compared with the existing research data, it is observed that though, the values of residual stress obtained do not exactly match with real time values, still the graphical behavior shows consistency with the real time stress behavior.





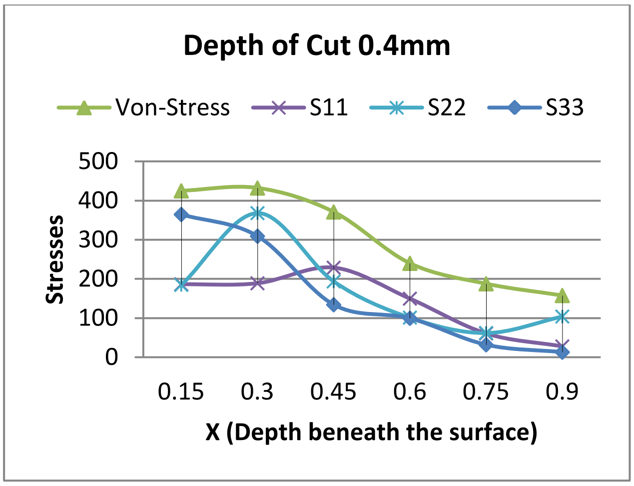


Fig 5: Graphical behavior of Residual stress plotted against depth beneath workpiece surface.

8. CONCLUSION

A numerical model is developed using finite element model using Abaqus v6.10 FE-code. The focus of result presented in this work is on simulated values of residual stress induced in work piece materials. The result of simulation shows closer agreement with real time behavior. Also generalized simulation procedure is proposed which can be useful for end application. Hence, it is concluded that finite element based simulation of orthogonal machining process is a robust approach and can be utilized with reasonable method of accuracy. This will eliminate the need of time consuming and costly experimental setup which is proposed in some of the research work. The simulation results can be utilized to optimize the machining process parameters so as to minimize induced residual stress, increased tool life and achieve better surface finish.

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