

Modeling Residual Stress and Workpiece Quality in Machined Surfaces

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Abstract

The increasing drive for productivity improvements and consistent part dimensionality in aerospace structures has led to the advent of machined monolithic parts. High speed machining technology employed affords the manufacture of thin-walled parts from single billets of material, resulting in the removal of approximately 85% of the initial workpiece material. With thin-walled monolithic parts come the increased propensity for workpiece distortion and few arresting mechanisms for crack propagation, largely due to potentially unfavorable residual stress states. These imposed states of stress can be a result of the machining conditions used (e.g., feeds, speeds and cutter geometry). A general method is presented to model the residual stress state induced by metal cutting operations which takes into account workpiece thermo-mechanical properties, cutter geometry and process parameters. In this paper the model is specifically applied to Al7050. Results indicate the magnitude and sign of the state of stress is shown to have no intuitive correlation to machining process parameters such as speed and chip load. Similar results are shown for stress-induced bending moments, a potential strong contributor to part distortion. In addition, the machining-affected layer is shown to be on the order of 1mm, easily on the same length scale as the wall thickness of aerospace structures.

1. INTRODUCTION

In order to improve metal cutting processes, i.e. lower part cost, it is necessary to model metal cutting processes at a system level. A necessary requirement of such is the ability to model interactions at the tool chip interface and thus, predict cutter performance. Many approaches such as empirical, mechanistic, analytical and numerical have been proposed. Some level of testing for model development, either material, machining, or both is required for all. However, the ability to model cutting tool performance with a minimum amount of testing is of great value, reducing costly process and tooling iterations. In this paper, a validated finite element-based machining model is presented and employed to determine the effects of cutting process parameters such as speed and chip load on the induced state of residual stress.

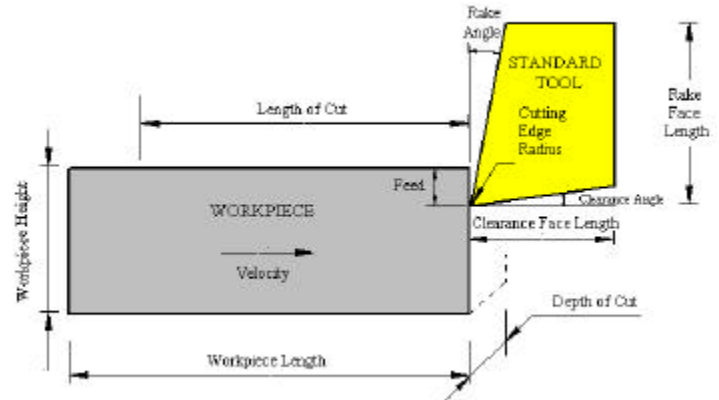


Figure 1 Schematic of orthogonal cutting conditions.

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 [1,2]. Techniques typically used a predetermined line of separation at the tool tip, propagating a fictitious crack ahead the tool. This method precludes 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 remeshing techniques to resolve the cutting edge radius [3,4]. Eulerian approaches, tracking volumes rather than material particles, did not have the burden of rezoning distorted meshes [5]. However, steady state free-surface tracking algorithms were necessary and relied on assumptions such as uniform chip thickness, precluding the modeling of milling processes or segmented chip formation .

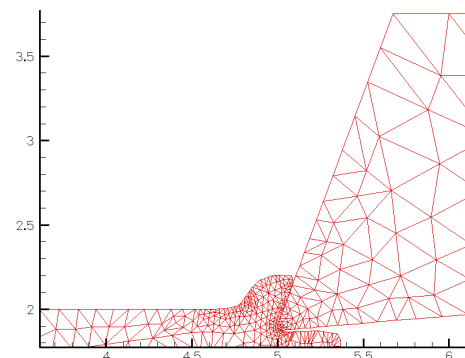


Figure 2 Initial tool indentation

In this paper, a Lagrangian finite element-based machining model is applied to orthogonal cutting of Al7050. Techniques such as adaptive remeshing, explicit dynamics and tightly couple transient thermal analysis are integrated to model the complex interactions of a cutting tool and workpiece.

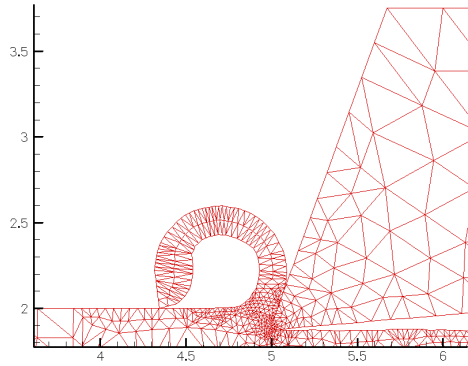


Figure 3 Chip formation

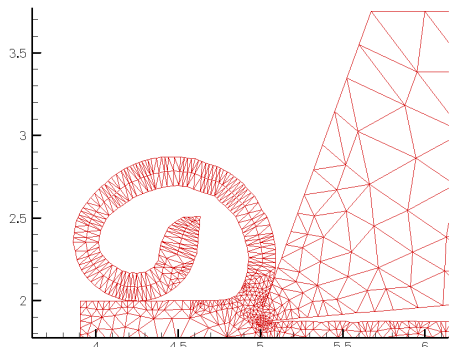


Figure 4 Fully developed continuous chip

2.2 Machining Simulation System

Simulations were performed with Third Wave Systems **AdvantEdge** machining simulation software, which integrates advanced finite element numerics and material modeling appropriate for machining. The orthogonal cutting system is described in Fig. 1 where the observer is in the frame of reference of the cutting tool with the workpiece moving with velocity v . The cutting tool is parameterized by rake and clearance angles, and a cutting edge radius, but can also accommodate general chip breaker geometries. In the plane strain case the depth of cut into the plane is considered to be large in comparison to the feed. The cutting tool initially indents the workpiece, Fig. 2, the chip begins to form Fig. 3, and finally curls over hitting the workpiece ahead of the cut, Fig. 4.

2. MODELING APPROACH

2.1 Finite Element Analysis

AdvantEdge [6], is an explicit dynamic, thermo-mechanically coupled finite element model specialized for metal cutting. Features necessary to model metal cutting accurately include adaptive remeshing capabilities for resolution of multiple length scales such as cutting edge radius, secondary shear zone and chip load; multiple body deformable contact for tool-workpiece interaction, and transient thermal analysis. For example, in the vicinity of the cutting edge radius the workpiece material is allowed to flow around the edge radius. The initial mesh, Fig. 5, becomes distorted after a certain length of cut, Fig. 6, and is remeshed in this vicinity to form a regular mesh again, Fig. 7. For a comprehensive discussion on the numerical techniques

the reader is referred to Marusich and Ortiz (1995) and to Marusich (2000) for validation examples.

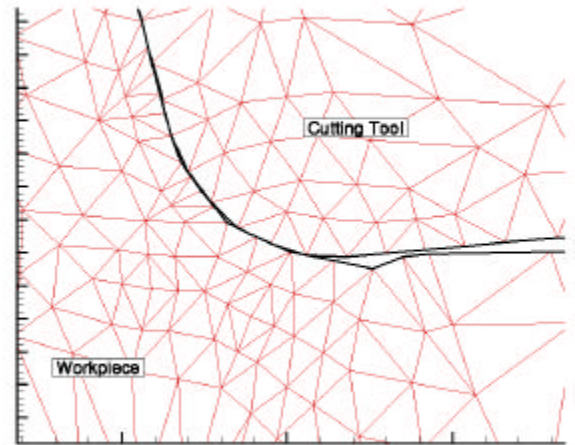


Figure 5. Initial mesh magnified in the cutting tool edge vicinity.

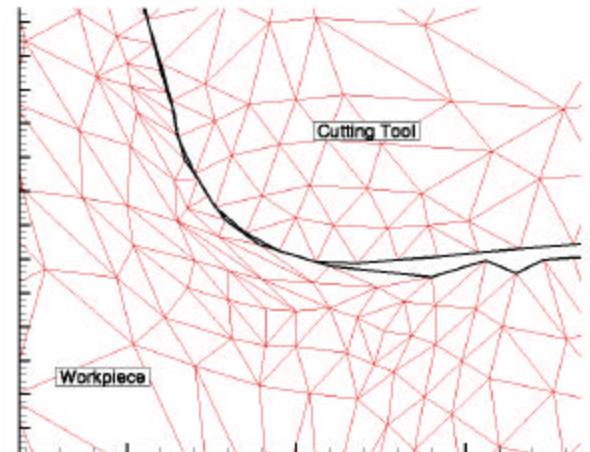


Figure 6 Deformed mesh.

Due to the transient thermal and dynamic behavior of the model it is necessary to thermo-mechanically relax the workpiece after the cutting process to accurately model the state of residual stress. The milling operation modeled is idealized by a single cutting tooth in a plane strain, orthogonal cutting, mode with a constant chip load, typically set to be the maximum in the cut.

2.3 Material Modeling

In order to model chip formation, constitutive modeling for metal cutting requires determination of material properties at high strain rates, large strains, and short heating times and is quintessential for prediction of segmented chips due to shear-localization [7,8]. Specific details of the constitutive model used are outlined in [3]. The model contains deformation

hardening, thermal softening and rate sensitivity tightly coupled with a transient heat conduction analysis appropriate for finite deformations.

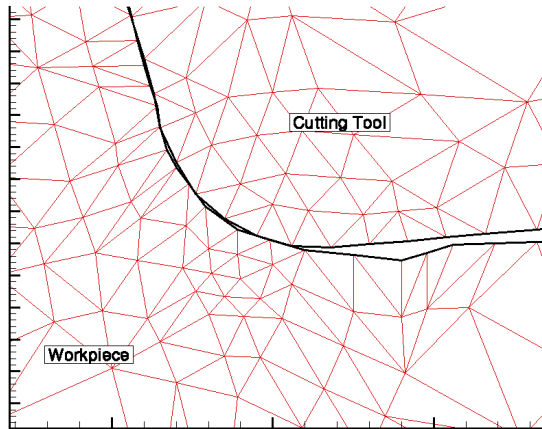


Figure 7. Updated mesh.

3. EXPERIMENTAL SETUP AND PREDICTIVE COMPARISON

Machining tests were conducted at Boeing on a round bar of Al7050 via end turning. Measurements of residual stress were taken at four equally spaced locations on the machined face of the bar. Strain gages with center holes were positioned on the bar face and material was removed using a hole drilling technique. During the facing of the bar the rotation of the workpiece was stopped over the course of one complete revolution. Due to this fact the effective chip load on the machined face varied linearly from maximum chip load to zero.

A typical set of residual stress measurements is given in Fig. 8. The tangential residual stress profiles at four positions (pos 1-4) as a function of axial depth into the bar are plotted. Comparison with simulation predictions over the same scale is also provided. It is noted that the decay in residual stress accompanies the decrease in chip load due to the stoppage of the workpiece in one revolution. Simulations were performed at the maximum chip load condition. Peak values appear to correlate well with the model, predicting the maximum location at a somewhat deeper position into the workpiece. Discrepancies in predicted effects near the surface are possibly due to smoothing of stress data from the integration points to the nodes, inaccurate characterization of the cutting tool edge and a loss in accuracy of the hole drilling technique near the surface.

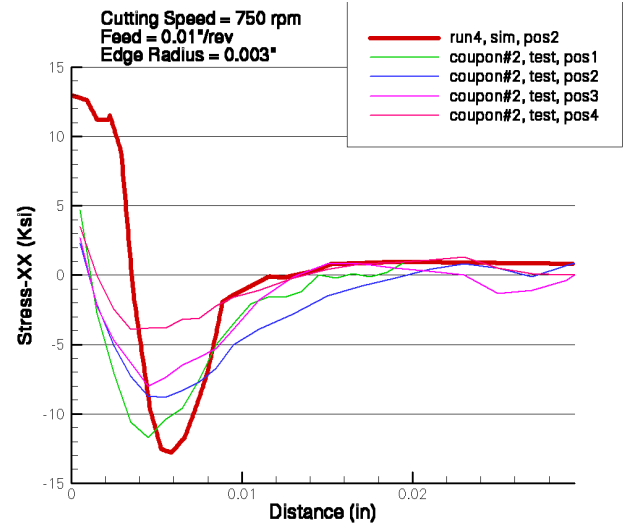


Figure 8 Comparison of tangential residual stress at four locations on machined face with model at maximum chip load condition

4. RESULTS

Residual stress predictions were made for several cutting conditions, varying speed, chip load and radial rake angle, Table 1. The normalized residual stress is plotted as a function of depth from the workpiece surface, Fig. 9. While no clear trend with process parameters is evident, two distinct residual stress signatures appear. Singling out three cutting conditions and comparing with the baseline conditions the two distinct stress signatures are apparent, Fig 10. A resulting bending moment per unit length can be computed from the stresses and plotted as a function of speed and chip load for the four cases, Fig. 11. Finally, the normalized moment is plotted as a function of tangential cutting force for all the cutting conditions, Fig. 12.

Table 1. Cutting conditions

Case	Chip Load per Tooth (mm)	Cutting Speed (m/min)	Tool Geometry
1	0.2	275	12° rake
2	0.4	138	12° rake
3	0.4	275	12° rake
4	0.2	275	25° rake
5	0.2	550	12° rake, 50mm dia.
6	0.4	550	12° rake, 50mm dia.
7	0.2	138	12° rake
8	0.3	275	12° rake
9	0.3	138	12° rake
10	0.1	275	12° rake

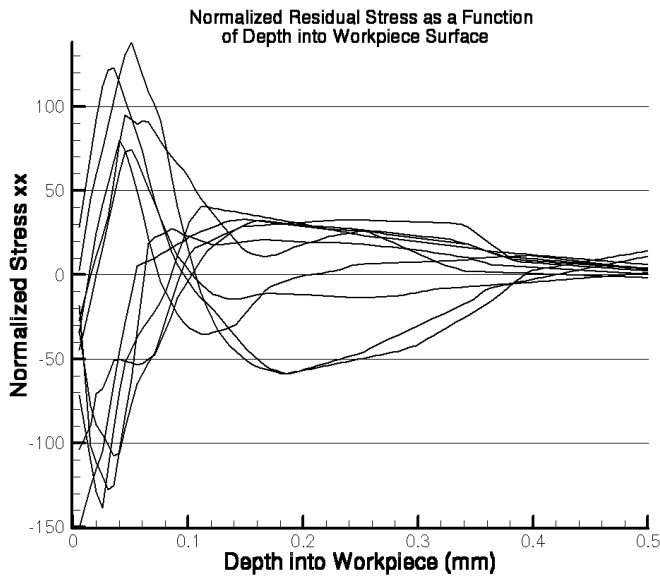


Figure 9. Family of predicted residual stress profiles as a function of depth into the workpiece.

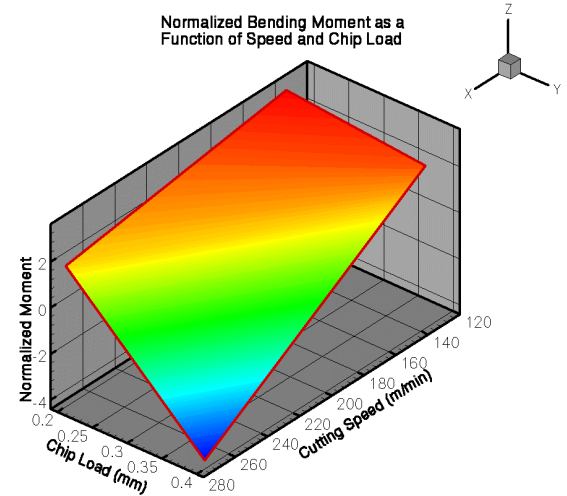


Figure 11. Normalized bending moment as a function of cutting speed and chip load for select cutting conditions.

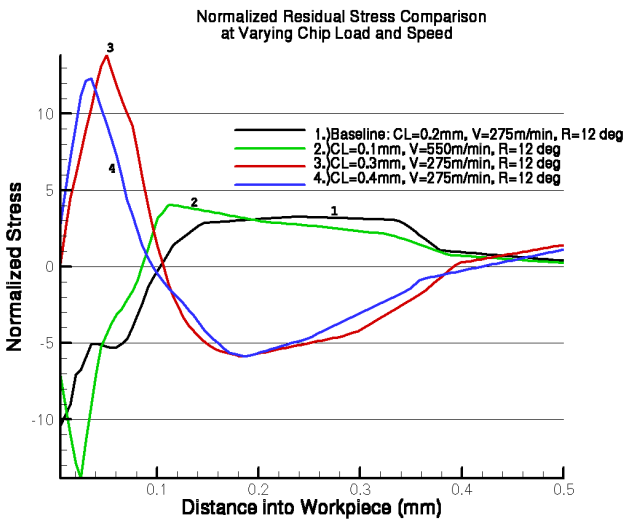


Figure 10. Select cutting conditions tested with substantially different residual stress signatures

5. DISCUSSION

The residual stress profiles for the entire test matrix are plotted as a function of depth into the workpiece, Fig. 9. The profiles typically decay to zero around 0.5mm beneath the workpiece surface, varying from positive to negative in order to satisfy equilibrium. Since thin walled aerospace parts can be on the order of a couple of millimeters in thickness, the machined-affected zone can be significant. When looking for correlation with process parameters, residual stress profiles were analyzed over a range of chip loads, cutting speeds and a pair of rake angles and exhibited no clear trends. Stress profiles in this parameter space appear to be most influenced by the chip load rather than speed or rake angle. The bending moments

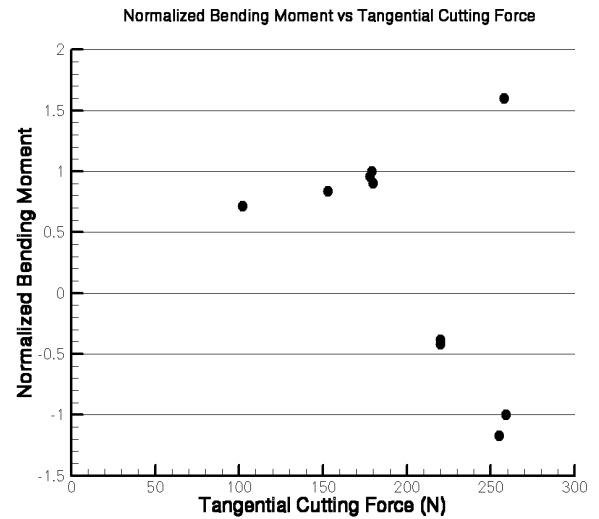


Figure 12. Normalized bending moment as a function of tangential cutting force for 10 different cutting conditions.

computed for these cases show a change in sign, i.e. an opposite tendency for bending, when the chip load is increased from 0.1mm to 0.3mm per tooth, Fig. 11. However, when the entire test matrix is plotted against tangential cutting force there appears to be either no trend or a bifurcation point, Fig 11.

6. CONCLUSION

A general method is presented to model the residual stress state induced by metal cutting operations which takes into account workpiece thermo-mechanical properties, cutter geometry and process parameters. In this paper the model is specifically applied to Al7050. Results indicate the magnitude and sign of the state of stress is shown to have no intuitive

correlation to machining process parameters such as speed and chip load. Similar results are shown for stress-induced bending moments, a potential strong contributor to part distortion. In addition, the machining-affected layer is shown to be on the order of 1mm, easily on the same length scale as the wall thickness of aerospace structures.

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