SIMULATION AND ANALYSIS OF CHIP BREAKAGE IN TURNING PROCESSES

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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 (Ehmann *et. a., 1997*). 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 calculate chip geometry, chip breakage, cutting forces, and effects in work-hardened workpiece surface layers.

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 (Strenkowski and Carroll, 1985; Komvopoulos and Erpenbeck, 1991; Sehkon and Chenot, 1993; Obikawa and Usui, 1996; and Obikawa *et. al* 1997.). 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 (Sehkon and Chenot, 1993; and Marusich and Ortiz, 1995). Eulerian approaches, tracking volumes rather than material particles, did not have the burden of remeshing distorted meshes (Strenkowski and Athavale, 1997). However, steady state free-surface tracking algorithms were necessary and relied on assumptions such as uniform chip thickness, not allowing the modeling of milling processes or segmented chip formation .

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In this paper, a Lagrangian finite element-based machining model is applied in to predict chip breaking processes in AISI4130. First, the orthogonal cutting model is validated against cutting forces and chip thickness. Second, a chip breakage criterion is implemented and validated against a range of cutting conditions and cutter geometries. Techniques such as adaptive remeshing, explicit dynamics and tightly coupled transient thermal analysis are integrated to model the complex interactions of the cutting tool and workpiece.

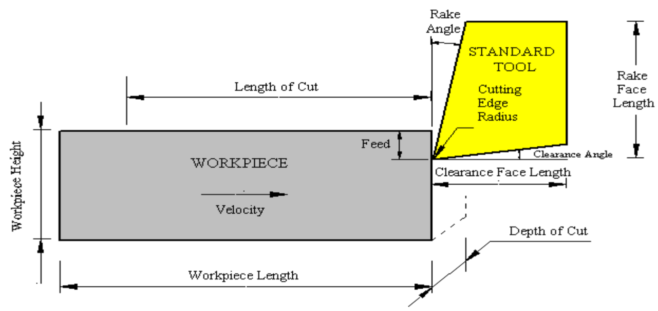

Figure 1 Schematic of orthogonal cutting conditions.

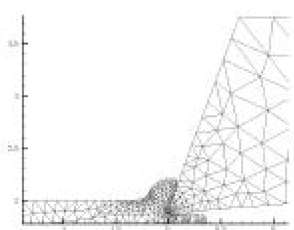

Figure 2 Initial tool indentation

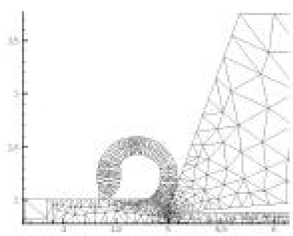

Figure 3 Chip formation

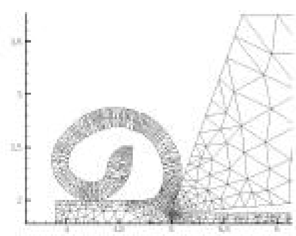

Figure 4 Fully developed continuous chip

Simulations were performed with Third Wave Systems ***AdvantEdge*** finite element based modeling software, which integrates advanced finite element numerics and material modeling for customize for machining applications. 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*. A user-defined geometry and cutting edge radius parameterize the cutting tool. In the plane strain case the depth of cut 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.

MODELING APPROACH

Third Wave ***AdvantEdge*** is an explicit dynamic, thermo-mechanically coupled finite element modeling package 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.

A major thrust of this paper is the investigation of cutting forces, chip formation and breakage, and work-hardened surface layer of the workpiece. In order to resolve the critical length scales necessary in the secondary shear zone and the inherent large deformations while maintaining computationally accurate finite element configurations, adaptive remeshing techniques are critical. Near 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).

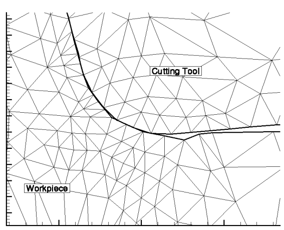

Figure 4 Initial mesh.

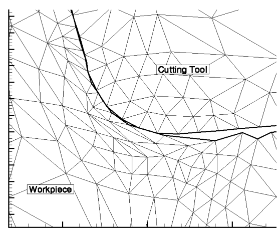

Figure 6 Deformed mesh.

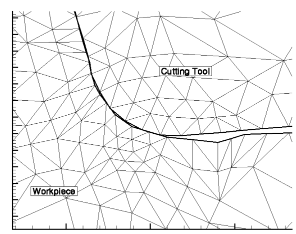

Figure 7 Updated mesh.

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 (Sandstrom and Hodowany 1998; Childs, 1998). The reader is again referred to Marusich and Ortiz (1995) for specific details of the constitutive model adopted. The model contains deformation hardening, thermal softening and rate sensitivity tightly coupled with a transient heat conduction analysis appropriate for finite deformations.

There is substantial material test information available in terms of deformation hardening, thermal softening and high strain rate response. Typical properties found in the open literature were used for model development (e.g., thermal conductivity, heat capacity and strain rate sensitivity). Compression tests were performed on the 29 HRc hardness material to obtain the true stress vs. true strain curve. Frictional characteristics are best determined at low cutting speeds where effects of the secondary shear zone become less dominant.

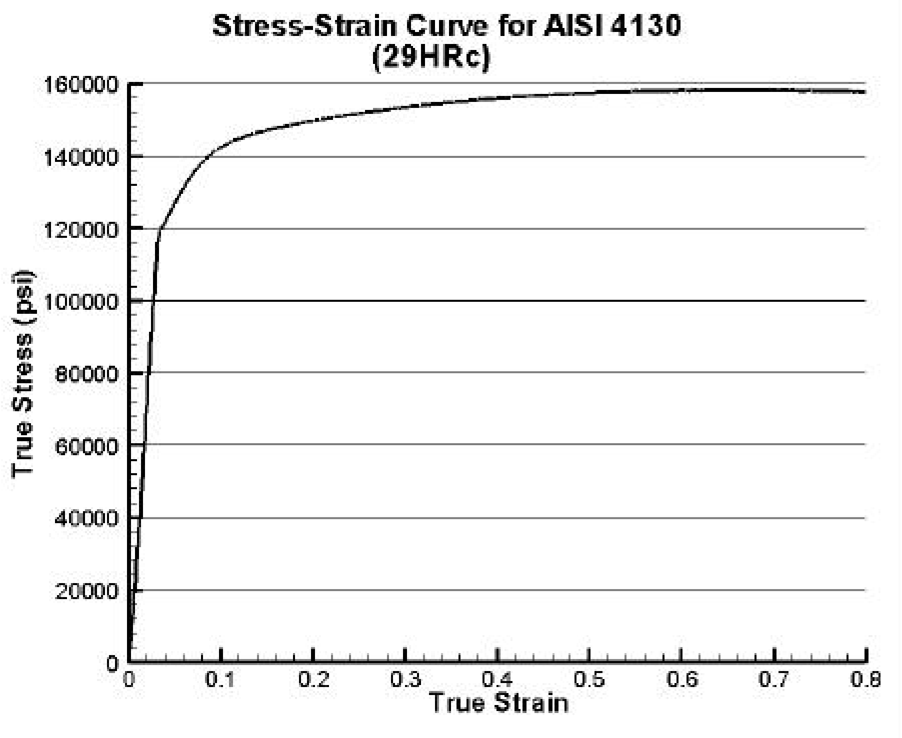

Figure 8 True stress vs true strain curve for AISI 4130 in HRc 29 hardness condition.

MODELING VALIDATION

The primary metrics for validating the models are cutting forces and chip thickness. Comparison over a wide range of industrially accepted cutting conditions establishes the efficacy of the numerical-constitutive integration response when compared with orthogonal tube turning tests. Once the models have been validated further analysis may be performed over a wider range of conditions, taking advantage of the first principals approach.

FORCE AND CHIP COMPARISON

Cutting force components tangential and normal to the cutting direction were compared to those generated during orthogonal tube turning in the case of AISI 4130. Cutting conditions for AISI 4130 are shown in Table 1.

Table 1 Cutting conditions for AISI 4130 validation

Case	Rake Angle	Feed mm/rev	Speed m/min
1	-7^{0}	0.1	300
2	5^{0}	0.1	300
3	-7^{0}	0.3	300

4	5^0	0.3	300
5	-7^0	0.1	150
6	5^0	0.1	150
7	-7^0	0.3	150
8	5^0	0.3	150
1CB	Chip Breaker	0.1	150
2CB	Chip Breaker	0.3	150
3CB	Chip Breaker	0.1	400
4CB	Chip Breaker	0.3	400

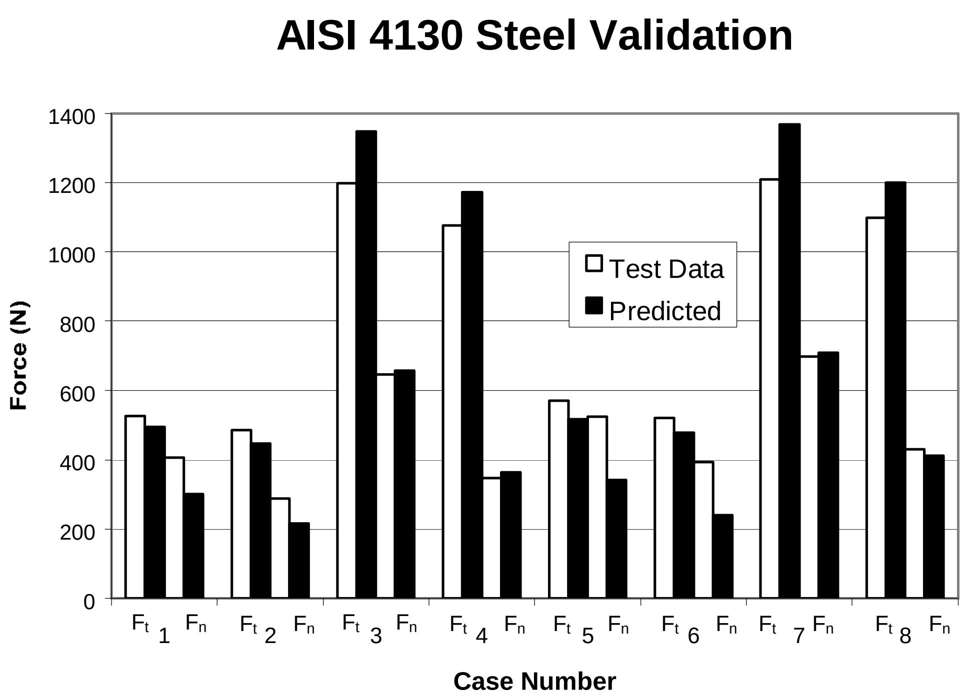

Figure 9 Comparison between predicted and measured force components over a range of cutting conditions for flat rake face cutters.

The predicted and measured cutting forces are compared for AISI 4130 in Fig. 9. The cutting conditions vary over a sufficiently large parameter space and establish confidence in the model results. Cutting forces, F_t , and feed forces, F_n , generally agree within 10% of the measured values, as well as the corresponding trends with changes in cutting conditions. Chip thickness provides an estimation of friction conditions. The corresponding comparison is made and again, agreement within 10% is obtained, Fig.10. Since the ultimate goal is to model chip formation and breakage with chip control inserts, a comparison of cutting forces for a Sandvik CCMT UM 4025 insert is provided, Fig. 11. The finite element model typically over predicts the cutting forces due to plane strain assumptions made, with numerical convergence of the mesh approaching from the "stiff" side of the solution. Once the material models have been validated, extrapolation to new cutting conditions (e.g., speed, cutter geometry) can be made with confidence due to the first-principles approach.

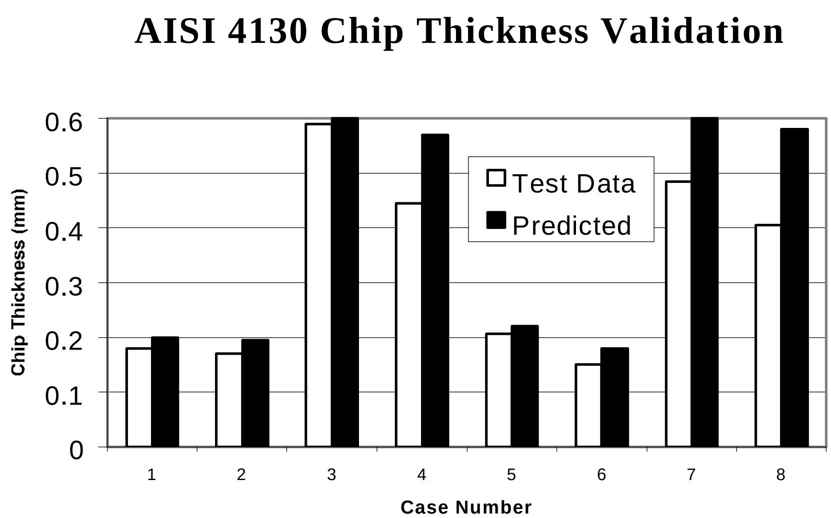

Figure 10 Comparison between predicted and measured chip thickness over a range of cutting conditions for flat rake face cutters.

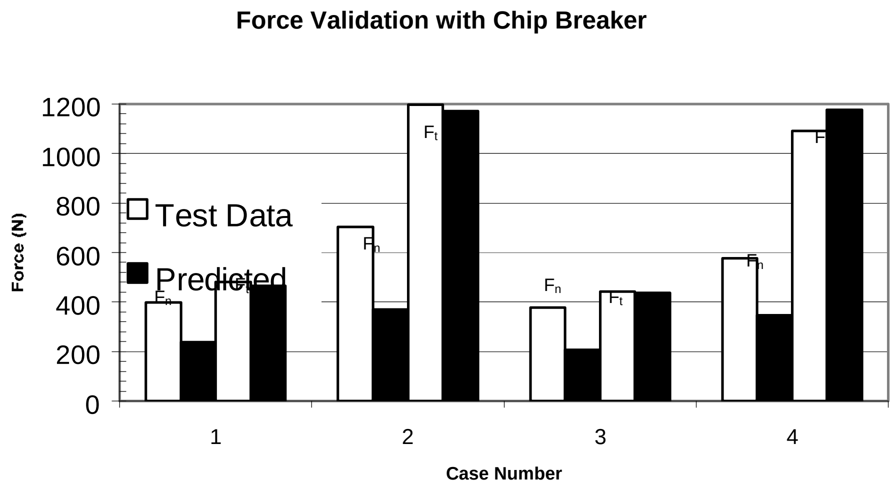

Figure 11 Cutting and feed force validation for AISI 4130 with Sandvik CCMT UM 4025 chip breaker**.**

CHIP BREAKAGE MODELING

Chip breakage is modeled as a tensile fracture event when the chip curls over contacts the workpiece ahead of the tool. The resulting bending moment induced in the chip due to contact causes areas of high tensile stress. In these areas the state of stress is compared against a maximum stress fracture criterion. If the maximum normal stress criterion is exceeded the chip is weakened locally via a damage model, Fig 12. The resulting local loss in strength becomes the dominant defect where the chip eventually breaks.

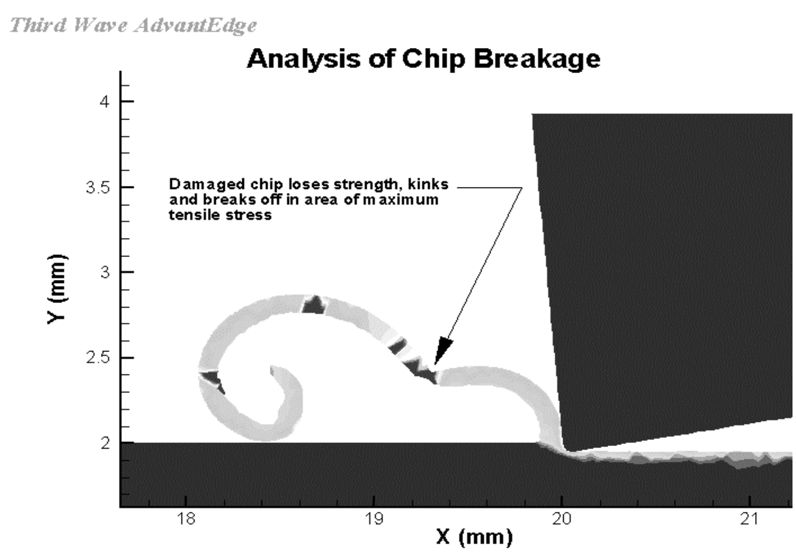

Figure 12 Location of defect in chip due to bending stresses induced by contact with the workpiece.

Comparisons of predictions of chip breakage and chip curl are made against test data generated with two different cutting tools over a range of cutting speeds. The fracture model was able to predict cases where chip breakage occurred as well as cases in which breakage did not occur. For the sake of interest, only cases for which chip breakage occurred are listed. The simulation and experimental results for two Sandvik inserts tested, CNMG 432-PF and CNMG 432-WM, are shown in Fig. 13 and Fig 14, respectively. Cutter profiles were taken at the depth of cut of 2.0mm for modeling purposes. In both cases chip breakage was predicted. The radius of curvature, or curl, of the predicted chips is compared with experiment, Fig. 15, for four cases in which chip breakage occurred. The feed range for the constant cutting speed tests where breakage was evidenced was 0.2-0.5 mm/rev.

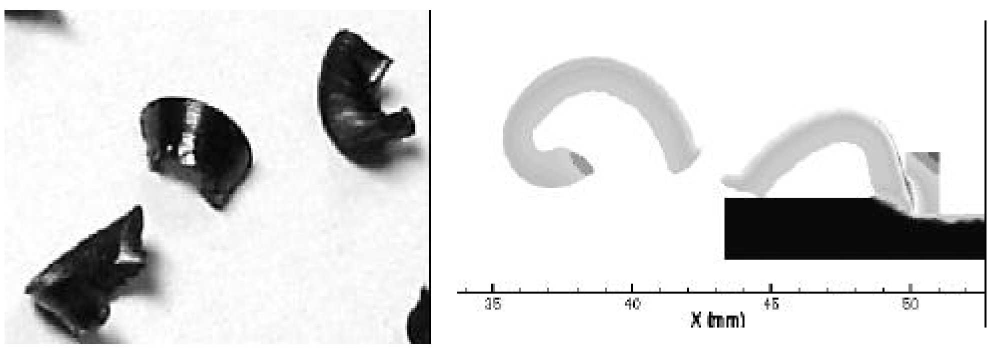

Figure 13 Comparison between actual and predicted chip breakage (photo courtesy of Caterpillar) for a Sandvik **CNMG 432-PF** type geometry insert. Cutting conditions are v=300m/min, f=0.5mm/rev and 2.0mm depth of cut.

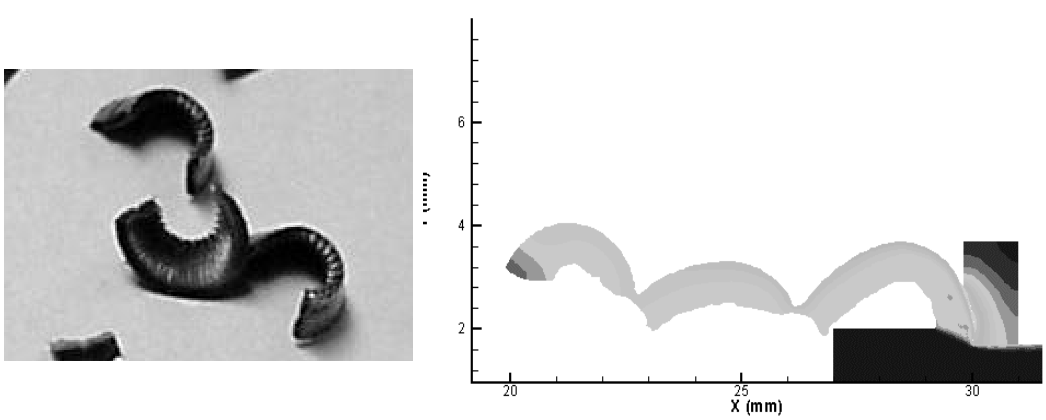

Figure 14 Comparison between actual and predicted chip breakage (photo courtesy of Caterpillar) for a Sandvik **CNMG 432-PF** type geometry insert. Cutting conditions are v=300m/min, f=0.3mm/rev and 2.0mm depth of cut.

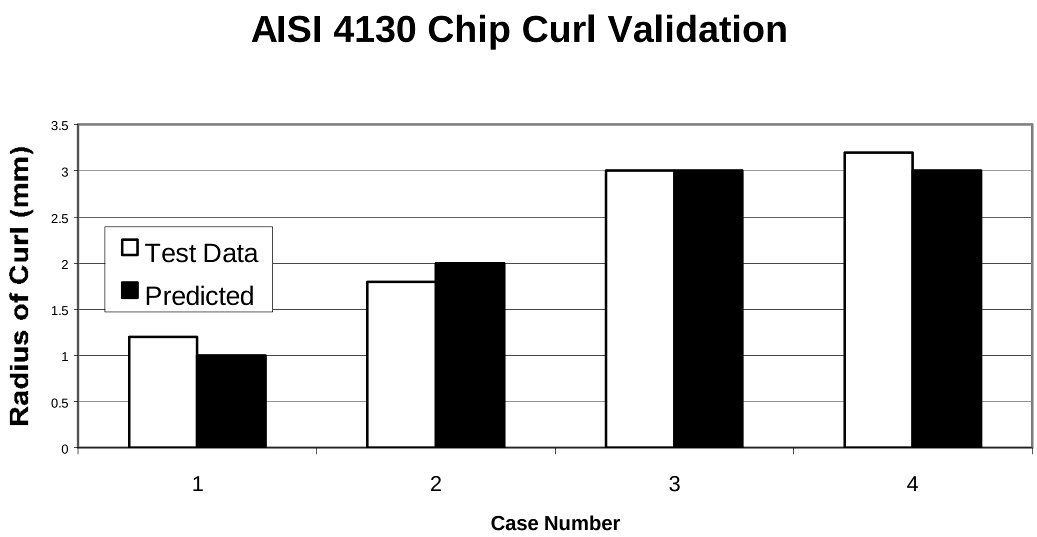

Figure 15 Comparison of radius of curvature, or chip curl, for model prediction against test for cases where chip breakage occurred.

Table 2 Cutting conditions for chip breakage validation

Case	Insert Geometry	Feed mm/rev	Speed m/min
1	CNMG 432-WM	0.5	300
2	CNMG 432-PF	0.3	300
3	CNMG 432-WM	0.2	300
4	CNMG 432-PF	0.5	300

CONCLUSION

A plane strain finite element model was utilized to model chip breaking in AISI 4130. The workpiece material was characterized using both low and high speed compression test data. Cutting force and chip thickness results were validated in orthogonal tube turning to establish the efficacy the constitutive model employed. A stress-based failure criterion was used to initiate a dominant flaw in the chip due to regions of large normal stress as a result of induced bending moments from contact with the workpiece. The chip breakage model was compared with cutting tests for two different chip breaker geometries over a range of speeds and feeds. Qualitative correlation for chip breakage between prediction and test was made for a number of cases. In the cases where chip breakage occurred, quantitative comparison of radius of curvature of the chips was made and good correlation was observed.

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