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Finite Element Analysis of Force Variation With Cutting Speed In Orthogonal Turning of Aluminum AA6351 Alloy

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Abstract

Aluminum alloys are finding extensive applications in aerospace industry. Cutting force estimation is indispensable with regard to machined surface quality, tool wear and power consumption. In the present work, finite element simulations have been carried out to estimate cutting forces and shear stresses in orthogonal turning of AA6351 aluminum alloy. Simulation results have been compared with corresponding experiments wherein cutting speed has been varied progressively. An almost excellent agreement is observed between simulation and experimental results, thus underscoring the utility of numerical procedures to fairly predict cutting force generation in machining.

Introduction

Aluminum alloys are increasingly replacing conventional metallic alloys as preferred materials for aerospace components. This can be attributed to the superior strength to weight and stiffness to density ratios of the aluminum alloys. Many of the components used in aerospace industry involve turning operations, hence indicating a need to fully understand orthogonal turning of aluminum alloys.

A number of analytical models have been proposed to estimate cutting forces in turning operations. Prominent theories include those by Merchant [1,2] and Oxley [3] (based on shear angle approach) and by Lee and Shaffer [4] (based on the slip line field theory). Later on, mechanisms like strain hardening, thermal softening and friction effects were also accounted for [5,6,7]. However, as per Mamalis et al [8], the above mentioned analytical models fail to consistently predict cutting forces due to a number of simplifying assumptions.

On the other hand, numerical procedures have provided viable alternatives to analytical techniques. Among many numerical methods, the finite element method (FEM) has been extensively applied due to its adaptability and accuracy of predictions. This method takes into consideration effects like strain hardening, thermal softening, tool-chip interface friction, large plastic deformations and strain rates etc. It gives quite reasonable estimates of cutting forces, shear and residual stresses, strains, strain rates, displacements/deformations, temperature distributions etc.

Finite element method was used to study steady state cutting by Usui and Shirakashi [9] and Iwata et al [10]. Strenkowski and Carroll [11] were the first to model chip formation and chip separation using FEM. Later, non-linear finite element schemes were utilized in orthogonal cutting modeling. Basically, two broad approaches were adopted by various researchers. First approach was Eulerian-based, which uses steady state cutting for simulations. The use of steady state cutting eliminates the requirement of a chip separation criterion. However, the chip morphology must be specified beforehand [12,13,14]. The Eulerian approach fixes the mesh in space, through which the work material flows during machining. This requires recalculation of element properties at every step. However, this technique avoids element distortion encountered during high strain rate machining.

The second approach is Lagrangian based [15-18], where cutting can be simulated from the initial state to steady state. Thus, chip formation can be effectively modeled. This method fixes the mesh with the material body, causing the mesh to get distorted with high plastic deformations. Chip separation criteria must be provided. A number of chip separation criteria have been implemented by various researchers, which will be discussed in the subsequent sections.

A number of researchers have used FEM to simulate force generation in turning [19-21]. Some have simulated subsurface damage in turning using FEM [22]. However, the surveyed literature shows that there is little simulation work done related to force prediction in turning of AA6351 alloy. Therefore, the present work was aimed at cutting force estimation in orthogonal turning of AA6351 alloy using FEM simulations.

Finite Element Modeling

Assumptions

In congruence with the previous research, this study also assumes a plane strain condition of orthogonal cutting. Next, the cutting tool is assumed to be perfectly rigid. This is done because the tool deflection is negligible in comparison to the enormous plastic deformations of the work. The cutting tool is also assumed to be perfectly sharp for the sake of effective simulations.

Problem geometry and finite element model mesh

The work and tool were modeled in the Geometric Modeler of the Ansys Explicit Dynamics module (Fig1). The workpiece was modeled as a rectangular slab. The slab cross-section conformed to the prescribed depth of cut in the out-of-plane direction. Its vertical dimension was in excess of the designated feed, to facilitate proper chip formation. The slab length was just enough to ensure steady state cutting. The cutting tool width matched the ‘workpiece-slab’ width, whereas its length in the cutting direction remained inconsequential. The tool geometry was provided with a suitable rake angle equal to the actual tool rake used in experimentation.

The cutting tool was meshed using the automatic method option available with the Ansys Explicit Dynamics Mechanical module, which is very appropriate for such simulations. The work piece meshing is required to be much finer, and so, the sizing method was utilized to create an even distribution of mesh element layers. The vertical edges of the work slab were divided into ten equal divisions, to ensure fine meshing.

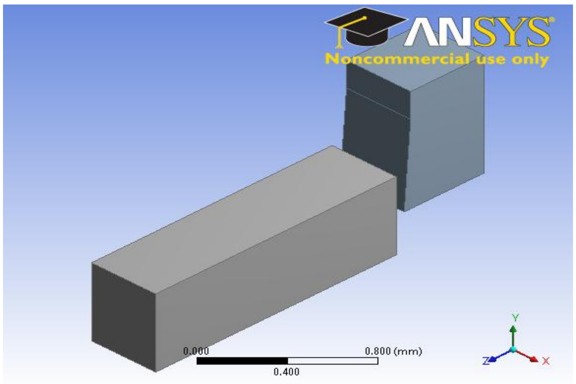

Figure 1: Tool-work geometry

Boundary Conditions

Following boundary conditions were prescribed for the simulations. The tool was allowed to move towards the workpiece with a constant velocity. Tool movement was restricted in vertical direction as well as in any direction in the horizontal plane, save the direction of prescribed velocity. The vertical faces of the workpiece normal to the tool approach were restricted in the cutting direction. However, these faces were not restrained in vertical direction. The bottom face of the work geometry was assigned as a ‘fixed support’, because it is a part of the larger workpiece being turned, and also because it is likely to experience very small deformation during machining.

Material model and temperature dependent properties

The strain rate effects as well as temperature dependent material properties are well represented by the constitutive equation of Johnson-Cook [23] as

$$k = \frac{1}{\sqrt{3}}[A + B\varepsilon^n][1 + C\ln\dot{\varepsilon}]\left[1\text{-}\left(\frac{T - T_r}{T_m - T_r}\right)^m\right]$$

wherein, values of material constants (A, B) and exponents (n, m) as well as melting temperature Tm were taken from published literature [24] (Table 1).

Table 1: Values of J-C equation for AA6351 [24]

A (MPa)	B (MPa)	n	C	m	Tm (°C)
102	200.9	0.415	0.002	1.05	582

Chip separation

Regarding chip separation, diverse criteria have been advocated by different researchers [25]. Some propound a distance based criterion that facilitates node separation at a prescribed distance from the advancing tool tip [9,26-28]. Others advocated a plastic strain based separation criterion, with typical values ranging from 0.6 to 1.5 [29,30]. Other criteria include those based on ductile fracture stress [31] and a combination of more than one criterion [32]. Huang and Black [33] in their study concluded that of all the different chip separation criteria and their combinations, the geometric strain criterion is best suited for steady state machining simulations. Hence, in the present work, chip separation is modeled using a geometric strain criterion [20]. This criterion provides for chip separation at the attainment of nodal strain equal to a preset limiting value.

Modified Coulomb friction law

Tool-chip interface friction was defined by a dynamic friction formulation based on Coulomb's law as follows (as provided in Ansys Help) –

$$\mu = \mu_d + (\mu_s + \mu_d)\, e^{-\beta v}$$

where,

μ_s is static coefficient of friction

μ_d is dynamic coefficient of friction

β is the exponential decay coefficient

ν is the relative sliding velocity at the point of contact

This model takes into account the effect of relative velocity between sliding surfaces on friction. Dynamic friction conditions are applied by selecting non zero values of the dynamic coefficient and the decay constant. In the present work, the applicable values of friction coefficient, dynamic coefficient and decay constant were selected from literature as 0.6, 0.4 and 0.1 [20, 34].

Simulation details

In this work, numerical simulations were performed using the Ansys/Autodyn explicit dynamics package. An augmented Lagrangian formulation (Ansys/Autodyn), appropriate for large strain rate deformations was selected in this study. Rate dependent material properties, appropriate boundary conditions, chip separation, friction modeling and work/tool geometries have already been discussed in the previous sections.

A total of 5 simulations were executed for 5 different cutting speeds (24, 31, 39, 47 and 55 m/min) at constant feed (0.25 mm/rev) and constant depth of cut (0.4 mm). Structural aluminum alloy (AA6351) was selected as the work material, while the tool was of carbide material. The tool rake was 4 degrees, and cutting was considered under dry conditions. All simulations were conducted with end times of at least 0.62 milliseconds to ensure steady state machining conditions [35].

Results and Discussions

All simulations were set to yield force distributions in the cutting direction. As can be seen from the simulation results (Fig.2-6), maximum cutting force contours are observed around the primary shear plane. The machined surfaces display maximum negative force contours, hinting at residual stresses due to compressive machining forces. In almost all cases, brittle discontinuous chip formation is observed, indicating high strain hardening due to cutting at low speeds. An overall increasing trend of cutting forces is observed. This could be credited to strain hardening induced high shear stresses generated in cutting.

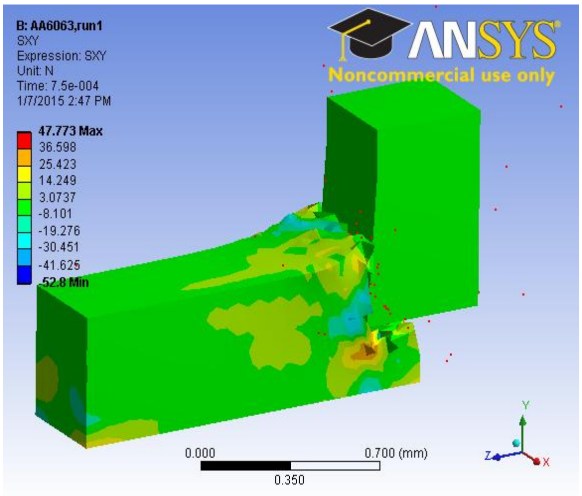

Figure 2: Cutting forces at speed 24 m/min, feed 0.25 mm/rev, depth of cut 0.4 mm

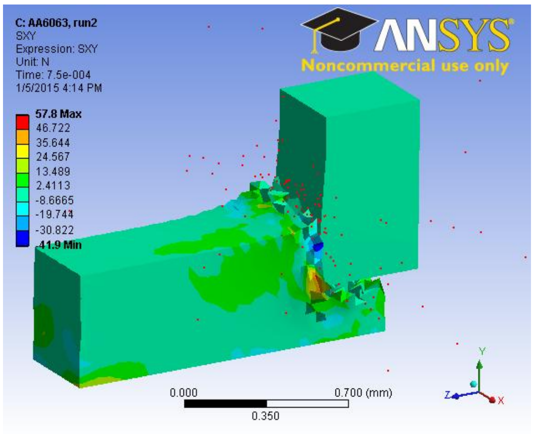

Figure 3: Cutting forces at speed 31 m/min, feed 0.25 mm/rev, depth of cut 0.4 mm

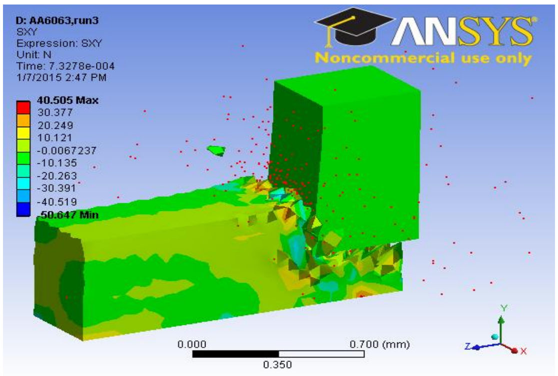

Figure 4: Cutting forces at speed 39 m/min, feed 0.25 mm/rev, depth of cut 0.4 mm

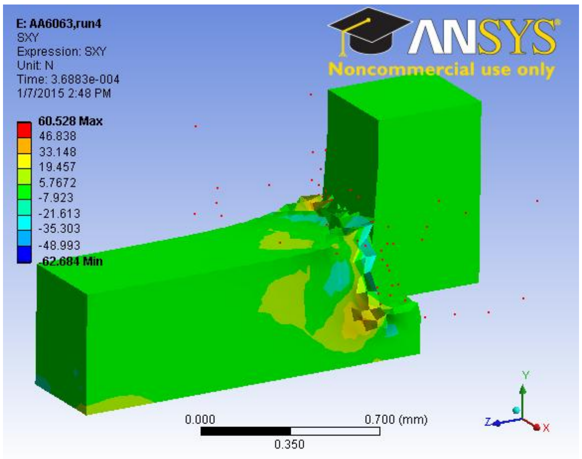

Figure 5: Cutting forces at speed 47 m/min, feed 0.25 mm/rev, depth of cut 0.4 mm

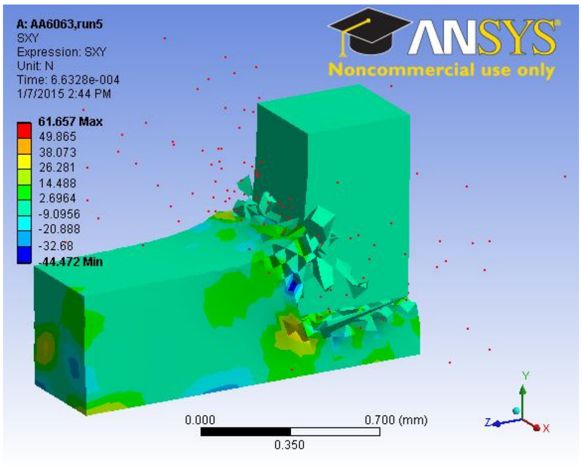

Figure 6: Cutting forces at speed 55 m/min, feed 0.25 mm/rev, depth of cut 0.4 mm

Comparisons with experimental data

As per the machining conditions set in the simulations, corresponding experimental runs were performed on the same set of work/tool materials. After each turning test, the generated chips were collected and chip thicknesses were measured by a micrometer. Then, chip thickness ratios, shear angles, friction angles etc. were computed to finally yield cutting force estimations for each run (Merchant, [1,2]).

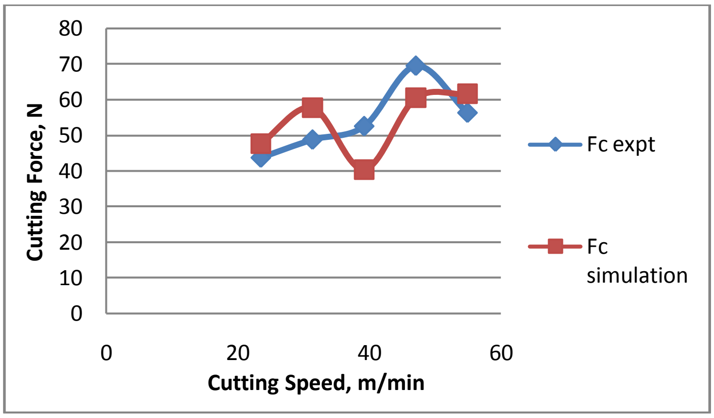

Figure 7: Comparison between simulated and experimental cutting forces.

Fig. 7 shows comparisons between simulated and experimental cutting forces for the machining conditions pertaining to the current study. It is evident from these comparisons that the finite element simulations are able to satisfactorily predict the cutting force generation in orthogonal turning under consideration. Similar results are reported across literatures in the related area [36]. The little errors in predictions may be ascribed to the assumptions made in the simulation procedures. For instance, by considering a realistic tool nose radius, better predictions may be obtained. Similarly, better tuned friction coefficients and finer meshing could yield improved results.

Conclusions

In this work, finite element simulations were performed to determine cutting forces in orthogonal turning of structural aluminum alloy. Appropriate simulation assumptions, models and settings based on published literature were implemented to obtain optimum results. The simulations predictions matched experimental data to a good degree, underscoring the relevance of finite element method in cutting force estimations. Thus, numerical methods like finite element analysis can be extensively used in industry to estimate cutting forces encountered in machining such aerospace alloys.

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