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Surface formation study using a 3-D explicit finite element model of machining of gray cast iron

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Abstract

Gray cast iron is the material of choice for machine tool structural components. However, since cast iron is a multiphase, anisotropic material it is difficult to machine to a high quality surface finish. To gain insight into the surface formation mechanisms during the machining of gray cast iron an explicit 3-D finite element cutting simulation was developed. To capture the anisotropic nature of gray cast iron flakes were modelled using zero thickness cohesive elements embedded in a pearlite matrix modelled using solid elements. The simulated cutting forces, surface formation, and finished surfaces were examined.

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Keywords: Surface integrity; Finite element method; Machining

1. Introduction

Gray cast iron is the material of choice for machine tool structural components due to its high stiffness, robust damping properties, and castability. The microstructure of gray cast iron consists of randomly distributed graphite flakes within a ferric matrix of pearlite and ferrite as shown in Figure 1.

Sliding guideways of machine tools require both extreme dimensional accuracy and a very even surface finish for high performance. Traditionally, a large grinder is used to finish the cast iron surface to meet surface quality requirements, but the grinding process is expensive, time consuming, and frequently leads to a production bottleneck at the surface preparation step due to the very low rate of material removal during grinding and multiple workpiece setups [1].

To improve productivity, an all milling based fabrication process for sliding guideways has been proposed [1]. The major roadblock to implementing this production strategy is achieving a consistent, even surface on the milled gray cast iron. This is due to stochastically dispersed surface irregularities that are generated during milling.

When milling an isotropic and ductile material, an approximate surface roughness value can be predicted using simple calculations that take into account tool geometry and cutting conditions. However, these calculations are not applicable to anisotropic cast iron, as the cavities greatly skew the surface profile, also shown in Figure 1. Past efforts into Finite Element (FE) modeling of cast iron [2,3] have focused on 2-D models that predict cutting force while no literature exists regarding the simulation of irregular surface feature formation during gray cast iron milling.

This research aims to expand upon the previous modeling work to create a 3-D FE model that can be used to gain insight into the surface formation mechanisms and expected finished surface characteristics of gray cast iron cut with a defined cutting edge.

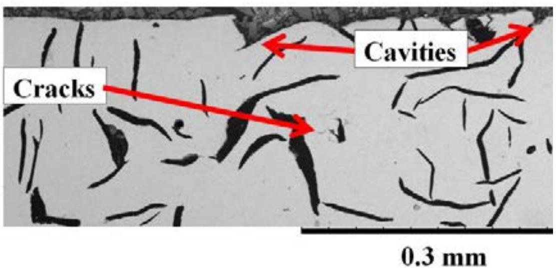

Fig. 1. SEM image of a cross section of gray cast iron with graphite flakes in black, pearlite in gray, and milling induced damage.

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2. Modeling Methodology

2.1. Geometry and meshing

Of primary interest in the study was the influence of the microstructure of the workpiece upon the final topology of the machined surface. Progressive polishing was used to capture the three dimensional geometry of the graphite flakes within the pearlite matrix. Hardened cast iron samples 70 mm by 40 mm and 1.5 mm thick were cut from the surface of large ingots using EDM. The hardened surface of the samples was ground flat using progressively finer abrasive paper mounted on a flat steel plate. Crocus cloth was then used to polish the flattened samples. Lastly, a Nitol solution was used to etch the sample surface. Etched samples were photographed using a Zeiss CSM 700 confocal microscope. The process was repeated a total of 10 times, removing 0.05 mm of material from the surface of the workpiece to a total depth of 0.5 mm.

Cast iron micrographs were analyzed using image processing software to create vector traces of graphite flakes in the plane of the micrograph. To facilitate meshing of the workpiece, the vector traces were simplified to remove features smaller than 0.025 mm.

The workpiece, Figure 2, was modeled as a rectangular prism with dimensions of 1 mm by 2 mm by 0.5 mm in the X, Y, and Z directions, respectively. The simplified vector trace of the graphite geometry at the surface of the cast iron samples was then overlaid on the top surface of the workpiece. Two planar partitions parallel to the XZ plane were created at 0.25mm offsets from the top surface of the workpiece. The simplified vector sketches of the graphite geometry obtained from the progressive polishing were then inserted onto the planar partitions. Using these vector traces as guides, the surface graphite vector traces were linearly extruded through the workpiece to create planar partitions within the workpiece. Planar partitions were edited to remove features less than 0.025 mm in size at their intersections to facilitate meshing of the graphite features.

To reduce the computational cost of the simulations, graphite flake partitions were only generated for the upper half of the modelled workpiece where plastic deformation and failure were expected.

Based upon convergence analyses conducted on 3-D cutting simulations using C45 steel workpieces the mesh in the workpiece was seeded using a local seed spacing of 0.025 mm on the graphite planar partitions and external edges

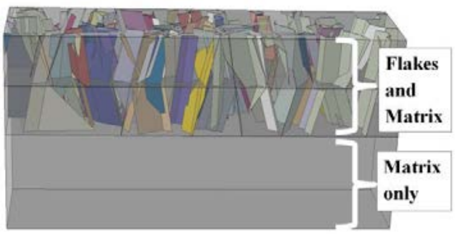

Fig. 2. Workpiece with planar partitions representing graphite flakes shown in color and matrix shown in gray.

of the upper half of the workpiece. In order to reduce the number of elements in the mesh, seeding in the lower half of the workpiece was linearly graded from 0.025 mm to 0.1 mm. A quadratic tetrahedral mesh was created from the mesh seeds using the default meshing algorithm in Abaqus.

It was observed in the micrographs of the gray cast iron that the graphite flakes were generally around 0.01 mm thick. To avoid the inclusion of extremely small elements which adversely affect the efficiency of computation and numerical accuracy and creating elements with very large aspect ratios, which yield poor results, the graphite was numerically modeled using linear cohesive wedge elements. In Abaqus, cohesive element behavior can be modeled as either continuum or traction separation. By using traction separation behavior, the surface tractions on the elements and relative displacements between the nodes on the primary sides of the elements are converted to stresses and strains using a constitutive element thickness that does not affect the stable time increment of numerical analysis. Cohesive elements are well suited to modeling zones where cracks are likely to develop, thereby lending themselves to representing the graphite flakes in gray cast iron. Cohesive elements with zero thickness were inserted into the solid mesh along the planar partitions representing the location of the graphite flakes within the workpiece. Tie constraints were generated between the mid-side nodes of the quadratic solid mesh and the linear cohesive elements.

The cutting tool was modelled as a 1 mm by 1 mm by 0.1 mm portion of a CBN milling insert with a 0.8 mm nose radius and 0.01 mm honed radius at the cutting edge. The tool was meshed with linear tetrahedral continuum elements created from a 0.05 mm mesh seeding.

2.2. Material properties

The pearlitic matrix was modeled using the Johnson-Cook plastic hardening [4] and damage [5] models. Johnson-Cook material models are commonly used when the effects of high strain rates and stress nature are important in modeling the mechanical behavior of a material. To calculate the plastic hardening, the current equivalent plastic strain of the material, strain rate effects, and the temperature of the material are all considered in the material model. The equivalent plastic strain at the onset of damage includes strain state effects based on the triaxial stress, the strain rate effect, and thermal effects.

Though both models include a thermal effect term, thermal effects were ignored in the current study to simplify model development. The Johnson-Cook parameters values for the model were referred from [2].

After the onset of damage the elements softened and eventually failed. The damage evolution was controlled by the fracture energy which was calculated using equation (1), referred from [6].