Microstructure-Level Force Prediction Model for Micro-milling of Multi-Phase Materials

A mechanistic model for the micro-endmilling process is developed that explicitly accounts for the different phases while machining heterogeneous materials. It is shown that frequencies in the cutting force signal higher than those that can be explained by the kinematics of the process can be explained by considering the multiple phases in the material. Experiments are performed on two compositions of ductile iron, pure ferrite and pearlite workpieces. These experiments show that the nature of the variation in the ductile iron cutting force signals can be attributed to the mixture of the phases. Additionally, simulation studies show that the frequency component of the variation is related to the spacing of the secondary (ferrite) phase and the magnitude of this component is determined by the size of the secondary phase particles. [DOI: 10.1115/1.1556402]

1 Introduction

Miniature components are needed for a wide range of applications from the aerospace to the biomedical industries. Many of these components contain complex three-dimensional features. Parts of the size of 500 µm (length, width) with holes 125 µm in diameter and wall thickness of 25–50 µm are now commonplace. Part materials include stainless steel, titanium, brass, aluminum, platinum, and iridium. Other applications include micro-drilling of 100 µm diameter holes for fiber optics, micro-milling of nozzles for high-temperature jets, and the micro-milling of molds and deep X-ray lithography masks. As precision and ultra-precision machining capabilities have been evolving to meet these needs, increasing attention is being given to micro-machining processes. Accordingly, models will be important to machine tool, cutting tool, and process design in micro-machining.

The milling process has proven to be a versatile process for the manufacture of complex components at the macroscale. Tusty and MacNeil [1] developed closed form expressions for the milling force assuming a circular tool path and a constant proportionality between cutting force and chip load. Other researchers have modelled the end milling process by discretizing the tool into axial slices and considering both circular [2] and trochoidal tool paths [3]. By discretizing the model, it is easier to incorporate complex cut geometries and varying cutting energies with chip thickness (the size effect). These models of the conventional milling process have led to an improved understanding of the force system and to improved process design.

Conventional milling process models have been applied to micro-milling with only limited success. To increase productivity in the micro-endmilling process, larger feedrates are desired [4]. However, other researchers [5] have selected very conservative feedrates in order to avoid tool breakage. These studies indicate that one obstacle to the economic utilization of the micro-milling process is the inability to select optimum process conditions in terms of both productivity and tool life. Recently, process models have been developed that attempt to overcome this hurdle by providing a more accurate force prediction at the micro-milling scale. Bao and Tansel developed a model for the micro-milling process that includes the effect of the trochoidal nature of the tool path [4], the effect of tool runout [6], and the effect of tool wear [7]. This model along with the conventional milling process models considers the workpiece material to be homogeneous.

As the depths of cut and feedrates are reduced, the chip load encountered in the process becomes the same order of magnitude as the grain size of many alloys. Whereas, in conventional milling processes, the workpiece material can be considered to be homogeneous and isotropic, in the micro-milling process, the workpiece material must be modelled as heterogeneous and, in some cases, anisotropic. Many commonly used materials such as steels do not behave in a homogeneous manner when considered at the length scales used in the micro-milling processes. Yuan et al. [8] experimentally found that the orientation of the SiC whiskers with respect to the cutting velocity had a significant impact on the diamond turning process. Recently, Chuzhoy et al. [9–11] developed a microstructure-based FEM model for the orthogonal cutting of ductile iron. By modelling the various metallurgical constituents—ferrite, pearlite, and graphite—separately, the authors were able to show the heterogeneous nature of machining such materials. In addition, the behavior of the phases, when machined individually, was seen to be very different. These studies indicate that at the process lengths considered in the micro-milling process range, the effect of workpiece microstructure should be considered.

As the tool moves from one metallurgical phase to another, it is expected that the cutting process will behave differently. These changes manifest themselves as force variations in the process that may lead to higher levels of vibration and accelerated tool breakage. In order to better understand the role of microstructure on the micro-milling process, a mechanistic model needs to be developed capable of handling multiple phases in the workpiece.

In this paper, a mechanistic model for the endmilling of heterogeneous materials is presented. Experimental force data was collected for the endmilling of two different compositions of ductile iron workpieces as well as for the endmilling of ferrite and pearlite workpieces. It is shown that the magnitude and variations of the forces resulting from endmilling ductile iron can be well predicted based on calibration experiments performed on only the pearlite and ferrite materials.
2 Model Development

In this section, a brief introduction of the traditional endmilling process model is presented. Then, the extensions to the model that enable it to handle machining heterogeneous materials are discussed.

2.1 Basic Milling Model. The underlying premise of the endmilling force model is that the process forces—the normal and friction forces on the rake face—are proportional to the chip load,

\[ F_N = K_N A_C = K_N b t C \]
\[ F_F = K_F A_C = K_F b t C, \]

where \( b \) is the width of cut and \( t_C \) is the instantaneous chip thickness. The specific energy terms, \( K_N \) and \( K_F \), are determined by a calibration process requiring a few cutting experiments. To use this model, the chip thickness needs to be accurately determined. In the model developed herein, the true kinematic profile of the tool path is considered in order to compute the chip thickness [6].

The endmill is discretized into axial slices and the chip thickness is computed for each slice. This discretization will facilitate the incorporation of the heterogeneous model enhancements described below. The cutting forces for each slice are determined and the total cutting forces are obtained through summation over all slices. For more details of the basic endmilling model, the reader is referred to Kline et al. [2].

2.2 Heterogeneous Material Model. In order to model the machining of heterogeneous materials, three additional capabilities must be included in the endmilling model. First, a three-dimensional mapping of the metallurgical constituents must be created that represents the microstructural composition of the workpiece material. Second, the location of the cutting edge with respect to that mapping must be determined in order to determine in which metallurgical phase, or phases, the tool is machining, along the engagement portion of the cutting edge. Finally, the specific cutting energy coefficients (\( K_N \) and \( K_F \)) in the cutting force-chip load relation must be obtained separately for each phase.

2.2.1 Generation of Microstructural Mapping. To model the micro-milling of heterogeneous materials, a mapping of the metallurgical phases must be created that represents the actual microstructure. In general, the number of phases that can be handled by the model is unlimited. In this study, ductile iron is used as a representative heterogeneous material. Ductile iron is composed of three distinct metallurgical constituents—graphite, ferrite, and pearlite. Graphite nodules are in the shape of spheroids and typically vary in diameter between 10 and 70 \( \mu m \). Ferrite is the ductile phase that encapsulates the graphite nodules. The surrounding matrix phase consists of pearlite—an alternating layer structure of ferrite and cementite. A photomicrograph of pearlitic ductile iron in shown in Fig. 1. In this figure, ferrite is the light colored material and pearlite is the darker region surrounding the ferrite. The graphite nodules can be seen contained within the ferrite regions. The sample shown in Fig. 1 contains approximately 50% ferrite with an average ferrite grain size of 70 \( \mu m \).

In this study, the microstructure is modelled by considering the secondary (ferrite) and tertiary (graphite) phases to be spherical in shape. The mapping of the microstructure is developed in a three-step process:

1. A cubic grid of points, \((x_i, y_i, z_i)\), is generated with a spacing equal to \( \delta r \). With a probability of \( p_i \), spheres used to represent the secondary and tertiary phases are then assigned to every grid point.
2. The coordinates of the grid points, \((X_i, Y_i, Z_i)\), are then randomly varied about their initial location according to a normal distribution with a mean of 0 and a standard deviation of \( \sigma_R \).

![Fig. 1 (a) Actual and (b) simulated microstructure of pearlitic ductile iron](image)

\[ X_i = x_i + u_x \sigma_R \]
\[ Y_i = y_i + u_y \sigma_R \]
\[ Z_i = z_i + u_z \sigma_R \]
\[ u_x, u_y, u_z \sim N(0,1). \]

The spheres used to model the secondary and tertiary phases are assigned radii, \( R_2 \) and \( R_3 \), respectively, that are normally distributed with means of \( \mu_2 \) and \( \mu_3 \), and standard deviations of \( \sigma_2 \) and \( \sigma_3 \), respectively.

\[ R_2 \sim N(\mu_2, \sigma_2^2) \quad R_3 \sim N(\mu_3, \sigma_3^2). \]

2.2.2 Location of Cutting Edge. In order to handle machining through different phases simultaneously, the end mill is discretized into axial slices as shown in Fig. 2. The position of the cutting edge of the \( j \)th slice, \((x_T, y_T, z_T)\), is calculated at each time step in the simulation for every flute engaged in the workpiece. This position is compared with the spheres used to represent the grain structure in the model. If

\[ R_3 < \sqrt{(x_T - X_i)^2 + (y_T - Y_i)^2 + (z_T - Z_i)^2} \]
\[ i = 1, \ldots, N_{\text{spheres}} \]
\[ j = 1, \ldots, N_{\text{slices}}, \]

then the cutting edge is located in the tertiary phase, and, therefore, the cutting coefficients for the tertiary phase are used. If the

![Fig. 2 End milling of ductile iron workpiece](image)
cutting edge is not in the tertiary phase for any of the spheres, then the cutting edge is located in neither the secondary nor tertiary phases, then the cutting coefficients for the primary phase are used.

The local normal and friction forces are then computed, by using Eq. (1), based on the appropriate cutting coefficients for that material phase in which the slice is currently machining,

$$d\sigma_F = K_N d\sigma_r = K_N t_C dz$$

where the subscript $k$ refers to the material phase (1 for primary phase, 2 for secondary phase and 3 for tertiary phase) whose cutting coefficients are to be used for that slice and $dz$ is the thickness of the axial slices. The axial slices are made sufficiently small to ensure that each slice is machining only one phase. The normal and friction forces are then transformed into local Cartesian forces ($F_T, F_R, F_Z$) in the rotating cutting edge coordinate system through the following equation,

$$
\begin{bmatrix}
  dF_T \\
  dF_R \\
  dF_Z \\
\end{bmatrix} =
\begin{bmatrix}
  -\sin \alpha_N & \cos \alpha_N \cos \beta & \cos \alpha_N \sin \beta \\
  \cos \alpha_N \cos \beta & \cos \alpha_N \sin \beta & \sin \alpha_N \sin \beta \\
  \sin \alpha_N \cos \beta & \sin \alpha_N \sin \beta & \cos \alpha_N \\
\end{bmatrix}
\begin{bmatrix}
  dF_N \\
  dF_F \\
  dF_{Nk} \\
\end{bmatrix} +
\begin{bmatrix}
  \cos \eta \cos \alpha_N \\
  \cos \eta \sin \alpha_N \cos \beta + \sin \eta \sin \beta \\
  \sin \eta \sin \alpha_N \cos \beta + \sin \eta \sin \beta \\
\end{bmatrix}
\begin{bmatrix}
  dF_{Nk} \\
  dF_{Fk} \\
  dF_{Nk} \\
\end{bmatrix},
$$

where $\eta$ is the chip flow angle determined from Stabler’s rule, $\beta$ is the helix angle, and $\alpha_N$ is the normal rake angle. The forces from Eq. (6) are then transformed into the global Cartesian coordinate system,

$$
\begin{bmatrix}
  dF_X \\
  dF_Y \\
\end{bmatrix} =
\begin{bmatrix}
  -\sin \theta & \cos \theta & 0 \\
  \cos \theta & \sin \theta & 0 \\
\end{bmatrix}
\begin{bmatrix}
  dF_T \\
  dF_R \\
  dF_Z \\
\end{bmatrix}.
$$

where $\theta$ is the angle of engagement shown in view A of Fig. 2. The forces due to all slices are then added to determine the total forces,

$$
F_X = \sum_{n_{flutes}} \sum_\xi dF_X
$$

$$
F_Y = \sum_{n_{flutes}} \sum_\xi dF_Y
$$

$$
F_Z = \sum_{n_{flutes}} \sum_\xi dF_Z.
$$

2.2.3 Calibration. In general, the cutting energies, $K_N$ and $K_F$, for each phase are assumed to depend on the chip thickness, $t_C$, the cutting velocity, $V$, and the normal rake angle, $\alpha_N$, in the following manner [12],

$$\ln K_N = a_{k0} + a_{k1} \ln t_C + a_{k2} \ln V + a_{k3} \alpha_N$$

$$\ln K_F = b_{k0} + b_{k1} \ln t_C + b_{k2} \ln V + b_{k3} \alpha_N.
$$

To fit these relations, tests with different chip thicknesses, cutting velocities and normal rake angles need to be performed. The average force in the normal direction and the average force in the friction direction are then found for one revolution of the tool. The average chip thickness, $t_{\bar{c}}$, for each experiment is computed,

$$t_{\bar{c}} = \frac{1}{\theta_{\text{exit}} - \theta_{\text{entry}}} \int_{\theta_{\text{entry}}}^{\theta_{\text{exit}}} t_C(\theta) d\theta,
$$

where $\theta_{\text{entry}}$ and $\theta_{\text{exit}}$ are the entry and exit angles of the cut, respectively. The value of $t_{\bar{c}}$, along with the average normal and friction forces, are used to determine the coefficients in Eq. (9). The average chip thickness is used only to determine the specific cutting energies in Eq. (9). The instantaneous chip thickness is used in Eq. (1) to predict the forces. In dealing with the machining of heterogeneous materials with multiple phases, each material, or phase, must be calibrated separately. This force modelling strategy allows for an accurate force prediction for each phase in a lumped approach, thus not requiring modelling of the separate force-generating mechanisms due to shearing, ploughing and elastic recovery that introduce more dependencies into the force model.

3 Experimentation and Validation

3.1 Microstructural Mapping. In order to model the micro-milling of a heterogeneous material, a mapping of the microstructure must be developed. In this study, a pearlitic ductile iron composed of approximately 50% pearlite (shown in Fig. 1(a)) and a ferritic ductile iron composed of approximately 70% ferrite (shown in Fig. 3(a)) were used.

By using the parameters listed in Table 1, microstructural maps were created for each ductile iron composition. The mean and standard deviation of the secondary/tertiary radii, as well as the standard deviation of the secondary phase spacing, were determined by analyzing the micrographs. The simulated pearlitic ductile iron map, of which a plane is shown in Fig. 1(b), contains 51.3% pearlite by volume. A plane of the ferritic ductile iron map containing 69.1% ferrite is shown in Fig. 3(b).

3.2 Experimental Setup. In order to verify the proposed modelling scheme, full slot end milling tests were performed on a micro-drilling/milling testbed at Northwestern University. The testbed utilizes a 110,000 rpm air spindle and three-axis motion control. Tests were performed on this machine with 500 $\mu$m diameter, 2-fluted carbide endmills with a 30° helix angle and a 9° radial rake angle. A Kistler dynamometer Model 9273 with a force detection threshold of 10 mN is used to collect the cutting force signals sampled at 32 kHz. A photo of the experimental setup and an endmill is shown in Fig. 4.

3.3 Model Calibration. In order to utilize the mechanistic model for machining multiple phase workpieces, separate sets of cutting coefficients must be determined for each phase in the

<table>
<thead>
<tr>
<th>Table 1 Parameters used to generate microstructural mapping</th>
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<tbody>
<tr>
<td>(in mm)</td>
</tr>
<tr>
<td>-----------------</td>
</tr>
<tr>
<td>Pearlitic D.I.</td>
</tr>
<tr>
<td>Ferritic D.I.</td>
</tr>
</tbody>
</table>

Transactions of the ASME

![Image](http://www.asme.org/terms/Terms_Use.cfm)
workpiece system. In order to model the phases present in many steels and irons, specially prepared samples of ferrite and pearlite were made and tested as described in Chuzhoy [9,10]. Two heats with different chemical compositions of both the pearlite and ferrite were obtained and tested to determine their stress-strain relationship. No significant difference was found between the two heats of ferrite or between the two heats of pearlite. Thus, it is believed that by determining the cutting coefficients for pearlite and ferrite, the machining of a wide range of steel and iron microstructures can be effectively modelled.

In this work, all tests were performed with the same endmill geometry and the same cutting velocity, so the specific cutting energies are assumed to depend only on the chip thickness. To fit the cutting coefficient relations in Eq. (9), full slotting experiments with a cutting velocity of 48 m/min, an axial depth of cut of 50 μm, and two feedrate values of 0.5 and 2.0 μm/tooth were performed for the ferrite and pearlite phases. The average force in the normal direction and the average force in the friction direction were computed for one revolution of the endmill. The average chip thickness, $t_C$, for each experiment was computed, and the value used to determine the coefficients listed in Table 2. A sample of the cutting forces and the fitted forces for are shown in Fig. 5 for the high feed ferrite calibration test.

Since only samples of pearlite and ferrite were obtained for cutting calibration tests, the cutting coefficients for graphite were estimated based on the relative magnitudes of Young’s modulus of 220, 190, and 25 MPa [9,10], for the pearlite, ferrite and graphite materials, respectively.

### 3.4 Model Validation

To determine the effectiveness of using the enhanced model to predict the forces in the microendmilling of a heterogeneous material, experiments on two compositions of ductile iron were performed with the same cutting conditions as those chosen for the calibration tests. The cutting forces were predicted by using the model and the cutting coefficients determined for the ferrite and pearlite materials. A spindle speed of 30,000 rpm, corresponding to a cutting velocity of 48 m/min, was chosen due to the limited sampling rate of the system being used and the desire to detect frequencies corresponding to the microstructure.

#### Table 2 Values of cutting coefficients

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Pearlite</th>
<th>Ferrite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_0$</td>
<td>8.60</td>
<td>7.85</td>
</tr>
<tr>
<td>$a_1$</td>
<td>-0.80</td>
<td>-0.65</td>
</tr>
<tr>
<td>$b_0$</td>
<td>-0.75</td>
<td>-0.65</td>
</tr>
<tr>
<td>$b_1$</td>
<td>-0.45</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

3.4.1 Pearlitic Ductile Iron. The pearlitic ductile iron cutting forces—feed direction parallel to X-direction and normal to feed direction parallel to Y-direction in Fig. 2, respectively—and their frequency spectra are shown in Fig. 6 for the high feedrate experimental condition. As the feedrate is increased from 0.5 μm to 2.0 μm, the magnitude of the experimental forces increases due to the increasing chip load. Besides the energy at the spindle frequency (500 Hz), the tooth passing frequency (1000 Hz), and their harmonics, there is a significant amount of the energy of the signal concentrated between 11 and 13 kHz in both tests. For a cutting velocity of 48 m/min, 12 kHz corresponds to a wavelength of 65.4 μm. This value is extremely close to the average ferrite grain size (2 μm) and spacing (δF) of 70 μm.

By including the pearlitic ductile iron microstructural mapping shown in Fig. 1(b) in the simulation, the model-predicted cutting forces and their spectra shown in Fig. 7 are generated for the high feed experimental condition. The force peaks in the cutting forces are at nearly identical locations for subsequent cutting edges since the feed per tooth (2.0 μm) is much less than the average size (70 μm) of the secondary phase particles. The cutting force spectra for the simulated data shown in Fig. 7 can be compared to the experi-
mental force spectra in Fig. 6. Note that the location of the frequency components between 11 kHz and 13 kHz is predicted well.

Since this model does not include any micromechanical modelling of dislocation motion across grain boundaries and does not consider the nature of the bonding between the metallurgical phases, it is believed that the difference in magnitude of these frequency components may be the result of these simplifications. The reader is referred to Chuzhoy et al. [9–11] in which a microstructure-based FEM was developed to model the orthogonal machining of heterogeneous materials.

3.4.2 Ferritic Ductile Iron. The ferritic ductile iron cutting forces also contain evidence of a microstructural influence on the cutting forces. Figure 8 shows the cutting forces and the frequency spectra from the low feed experiments on the ferritic ductile iron sample. Frequency components around 15 kHz corresponding to a wavelength of 53.3 μm are observed in the experimental data. This wavelength is close to the ferrite grain spacing (d_f) of 50 μm used to generate a microstructure with near 70% ferrite by volume.

Similarly, the predicted ferritic ductile iron cutting forces shown in Fig. 9 can be compared to the experimental cutting forces shown in Fig. 8. Although these frequency components are much lower in magnitude than those from the pearlitic ductile iron experiments, this is not unexpected due to the fact that the material is composed of predominantly ferrite and the variation in the cutting forces is due to the small amounts of graphite and pearlite in the sample. Thus, it appears that the multi-phase microstructure has a large effect on the forces in micro-endmilling, accounting for over a third of the energy in the cutting force signal.

In comparing the experimental data for each ductile iron material, it is observed that the frequency of the cutting force data is not affected by the feedrates, only the magnitude of the forces is affected. The magnitude of the simulated forces also matches well with the experimental forces. The peak-to-peak values of the feed force are within 20% and the normal force within 15%. However, the experimental ductile iron forces in the normal to feed direction become negative in the regions of small-uncut chip thickness. This is most likely due to disengagement of the tool from the workpiece as the force abruptly changes level. The variation in the machining forces encountered while moving from one phase to another phase can be considered to be a series of step changes on the endmill. The impact loads during the step changes will cause the endmill to deflect. Even the small displacements caused by these forces will deflect the tool enough to cause disengagement. The simulation model considers the endmill to be perfectly rigid, thus the predicted forces never become negative in the normal to feed direction. It is important to note that no calibration tests were performed on the ductile iron specimens, so the forces predicted in the simulation were the result of using the enhanced model and the calibration coefficients from the ferrite and pearlite experiments.

3.4.3 Homogeneous Material Machining. The model was also used to predict the cutting forces for the machining of single-phase ferrite and pearlite. The power spectra of the ferrite and pearlite forces, Figs. 10 and 11, respectively, do not show the energy at the frequencies above 10 kHz. The presence of the high frequency components in all the ductile iron experiments but not in the ferrite or pearlite tests is further evidence that these frequency components are due to the multi-phase ductile iron microstructure. Even though the dynamometer used in this study has a flat frequency response to approximately 4 kHz, above this frequency two signals can still be compared for the presence or absence of certain frequencies. The presence of the high frequency components in all the ductile iron experiments but not in the ferrite or pearlite tests indicates that these frequency components are due to the ductile iron material.
3.4.4 Application of the Model to Macro-endmilling. The pearlitic ductile iron microstructure used for the micro-milling process was used to simulate full-slot endmilling with a 12 mm diameter endmill with an axial depth of cut of 4 mm and a feedrate of 5 \( \mu \text{m} \) per tooth. The cutting forces and their spectra are shown in Fig. 12. In this figure, it is seen that the higher frequency harmonics are not present as compared to the micro-milling case (Fig. 6). This is due to the fact that the effect of the microstructure on the force variation is lost at the macro-level. As the length of contact between the tool and the workpiece increases, variations in the ratio of ferrite to pearlite become smaller during the engagement length of the cutting edge.

Explicitly modelling the ductile iron workpiece as a heterogeneous material in the micro-endmilling process results in a cutting force model that is capable of capturing the higher frequency components of the cutting forces representing microstructure-level effects. When machining with such small depths of cut and chip thicknesses, the perturbation to the machining force caused by the presence of the microstructure is increased when compared to the macro-machining processes. This is due to the fact that fewer grains are being cut at any time in the micro-machining processes than in the macro-machining processes. Therefore, the averaging effect of the different orientations and the different phases is lost in the micro-machining processes.

3.5 Correlation Between Surface Roughness and Force Variation. In order to further investigate the influence of microstructure on the micro-milling process, measurements were taken of the surface roughness at the bottom of the machined slots of both ductile iron samples and the pure-constituent ferrite and pearlite. This data was collected with a Wyko NT1000 optical profiler by utilizing a 20X magnification lens. A 301.7 \( \mu \text{m} \times 229.6 \mu \text{m} \) area was sampled with 0.4 \( \mu \text{m} \) and 0.7 \( \mu \text{m} \) resolution in the feed and normal to feed directions, respectively, near the center of each slot and the surface roughness parameter, \( R_a \), was computed. The measured \( R_a \) values for the experiments are listed in Table 3.

The \( R_a \) values in Table 3 show some expected and interesting trends. The \( R_a \) values for all workpiece materials show the expected increase as the feedrate is increased. In addition, both ductile iron surfaces exhibit a larger roughness than the single-phase ferrite and pearlite workpieces. Between the two ductile iron samples, the \( R_a \) values for the pearlitic ductile iron are larger than those for the ferritic ductile iron.

The increase in surface roughness for the ductile iron appears to be related to the amount of variation in the microstructure of the workpiece. The single-phase ferrite and pearlite workpieces possess the smallest \( R_a \) values. The ferritic ductile iron workpiece, which is composed of 70\% ferrite, has a larger roughness than both the ferrite and the pearlite workpieces. The sample with the most balanced mixture of the constituents, the pearlitic ductile iron, possesses the largest surface roughness values.

The relative surface roughness values for the different workpiece materials correlates well with the energy in the microstructure-related, higher frequency force signal components. As seen in Figs. 10 and 11, the ferrite and pearlite experiments

<table>
<thead>
<tr>
<th>Material</th>
<th>Low Feed</th>
<th>High Feed</th>
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<tbody>
<tr>
<td>Ferrite</td>
<td>0.10 ( \mu \text{m} )</td>
<td>0.17 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Pearlite</td>
<td>0.10 ( \mu \text{m} )</td>
<td>0.24 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Ferritic ductile iron</td>
<td>0.16 ( \mu \text{m} )</td>
<td>0.44 ( \mu \text{m} )</td>
</tr>
<tr>
<td>Pearlitic ductile iron</td>
<td>0.26 ( \mu \text{m} )</td>
<td>0.64 ( \mu \text{m} )</td>
</tr>
</tbody>
</table>
contained very little frequency components above 5 kHz. These materials also possessed the lowest $R_a$ values. The ferritic ductile iron cutting forces, shown in Fig. 8, contain more energy at the frequencies above 10 kHz than the pearlite and ferrite, but contain less energy than the pearlitic ductile iron cutting forces, shown in Fig. 6. This ranking of the higher frequency components in the cutting forces is the same as the ranking of the surface roughness values.

### 4 Effect of Microstructure Grain Size and Spacing on the Cutting Forces

Once the microstructure-level micro-endmilling model has been validated, it may be usefully employed to study the influence of microstructure characteristics on machining performance. Since the microstructure is found to be important in explaining higher frequency components of the cutting force system, a series of simulations were performed in order to study this relationship further. Both the size of the ferrite grains and the spacing of the ferrite grains were varied to determine their role in determining the force system.

Simulations were performed with the parameters for the ductile iron microstructure as shown in Table 4. The feed direction forces are shown in Fig. 13. The feed direction forces are high-pass filtered to remove the tooth passing frequency and the filtered data spectra are shown in Fig. 13 as well. In the simulated force plots, it is seen that as the spacing between ferrite grains is increased (compare Cases S1 and S2 to Cases S3 and S4), the steps in the force data occur less often. This is also shown in the frequency spectra plots as the higher frequency component shifts from 12 kHz with a 70 $\mu$m spacing to about 7 kHz with a 120 $\mu$m spacing.

As the size of the grains is increased the magnitude of the frequency components also increases. In comparing Case S1 to Case S2 and Case S3 to Case S4, it can be seen that the frequency due to the microstructure is not changed, but as the size of the second phase—in this case, ferrite—is increased, this frequency component increases in magnitude.

### Table 4 Microstructure variation study parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>$\delta_k$ [$\mu$m]</th>
<th>$\mu_2$ [$\mu$m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>70</td>
<td>20</td>
</tr>
<tr>
<td>S2</td>
<td>70</td>
<td>35</td>
</tr>
<tr>
<td>S3</td>
<td>120</td>
<td>20</td>
</tr>
<tr>
<td>S4</td>
<td>120</td>
<td>35</td>
</tr>
</tbody>
</table>

In summary, the frequencies present in micro-milling operations of heterogeneous materials may be explained by the spacing of the second phase, while the size of the secondary phase particles determine the strength of these frequency components.

### 5 Conclusions

From this paper, the following conclusions can be made:

1. A mechanistic model for the micro-endmilling of multiphase materials has been developed. This model explicitly considers the various phases in determining the magnitude and variation of the cutting force.
2. Calibration tests are performed for ferrite and pearlite, the major components of ductile iron and many other steels, in order to determine the machining force-chip load relationship for the individual phases of a heterogeneous material.
3. The model is validated by using the calibration information from the pearlite and ferrite to predict the cutting force magnitude and variation in the micro-milling of ductile iron. Both the magnitude and the nature of the variation compared favorably to the predicted data. No calibration tests are performed directly on the ductile iron specimens. This model is capable of predicting the higher frequency variation of the cutting force when micro-milling a multiple-phase material such as ductile iron. In micro-milling, the microstructural effects can account for more than 35% of the energy in the cutting force signal.
4. Through simulations, it is shown that the frequency of the variation can be attributed to the spacing of the secondary phase, while the size of the secondary phase is seen to affect the magnitude of this variation.

The approach of explicitly modelling the microstructure is not limited to microstructures that can be approximated as spherical in shape. The ability to model different shapes of microstructures can be easily accommodated; for example, ellipsoids can be used to model SiC whiskers in Al, and the model is already capable of modelling either spherical or cylindrical phases. The approach is also not limited to modelling alloys. Cylinders can be used to model fibers in reinforced composite materials.

The concept of utilizing a mapping to define regions that contain differently behaving material, is not restricted to modelling machining processes in which the material is heterogeneous at the micro-scale. A machining process on an assembled part of different materials can be handled in much the same way and an idea of the variation of the force can be obtained. For example, the milling of an aluminum cylinder head with a cast iron cylinder lining can be handled with the same concept, only at a macro-scale.

Capturing the variation in the cutting forces allow for a more complete picture of the excitation forces on the tool and the workpiece to be developed. This understanding is even more critical in the micro-milling process characterized by very small diameter tooling and thin workpiece features. An understanding of how the forces are affected by the microstructure will lead to better microstructure designs for miniature components as well as designing machining processes and tooling that perform more reliably in the presence of these force variations.

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References