On the Modeling and Analysis of Machining Performance in Micro-Endmilling, Part I: Surface Generation

This paper examines the surface generation process in the micro-endmilling of both single-phase and multiphase workpiece materials. We used 508 μm dia endmills with edge radii of 2 and 5 μm to machine slots in ferrite, pearlite, and two ductile iron materials at feed rates ranging from 0.25 to 3.0 μm/ flute. A surface generation model to predict the surface roughness for the slot floor centerline is then developed based on the minimum chip thickness concept. The minimum chip thickness values were found through finite element simulations for the ferrite and pearlite materials. The model is shown to accurately predict the surface roughness for single-phase materials, viz., ferrite and pearlite. Two phenomena were found to combine to generate an optimal feed rate for the surface generation of single-phase materials: (i) the geometric effect of the tool and process geometry and (ii) the minimum chip thickness effect. The surface roughness measurements for the ductile iron workpieces indicate that the micromilling surface generation process for multiphase workpiece materials is also affected by the interrupted chip-formation process as the cutting edge moves between phases resulting in burrs at the phase boundaries and the associated increases in surface roughness.

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workpiece be considered. The heterogeneity in the workpiece microstructure leads to significant variations in the machining process as the cutting moves from one phase to another. These variations affect the force system [19], leading to dynamic excitations of the tool-workpiece structural system, and affect the surface generation [14,20] and chip formation processes. Spath and Huntrup [20] showed that when machining a dual-phase steel, the different metallurgical phases—ferrite and pearlite—behave differently, leading to increased surface roughness and form error in the machined features.

In Part I of this paper, the roles that tool edge condition and workpiece microstructure, specifically multiple metallurgical phases, have on the floor surface generation in micromilling will first be examined through controlled experimentation. A model for the slot floor centerline surface generation process based on the minimum chip thickness concept will then be developed. The minimum chip thickness ratio values in the model will be determined through application of a finite element (FE) simulation tool. Experimental data for single-phase workpiece materials will be compared to predictions from this model. Additional data for the surface roughness of multi-phase materials will be presented.

2 Surface Generation Experimentation in Micro-Endmilling

2.1 Experimental Design. In order to study the influence of the tool edge condition and the workpiece microstructure on the slot floor surface generation as the endmilling process is scaled down to produce component features in the sub-mm size range, experiments were performed with 508 μm (0.020 in.) diameter endmills on workpiece materials with different microstructures over a range of feedrates. Four materials were selected for the experimentation: two specially-prepared, single phase materials (pure ferrite and pearlite) [21], and two multi-phase materials with different compositions of the two single phase materials. Micrographs of the ferritic and pearlitic ductile irons are shown in Fig. 1. The ferritic ductile iron is composed of approximately 70% ferrite, and the pearlitic ductile iron is composed of approximately 50% ferrite. The material behavior of the ferrite and pearlite samples was extensively characterized [22], and a FE simulation for ductile iron machining was developed based on modeling the behavior of the individual constituents [21,23].

Five-millimeter long, full-slot endmilling cuts were performed with the conditions listed in Table 1. Multiple levels of feed rate and axial depth of cut were chosen in order to study the interaction between ploughing and process condition effects on the surface roughness of the slot floor.

Due to the expected importance of the tool edge condition on the micromilling process, based on the diamond turning work of Lucca and Spath [15] and Lucca et al. [16,17] and the micromilling work of Kim et al. [12], the cutting edge radius of the tools was varied in the experimentation. In order to select appropriate levels for the tool edge condition, the geometry of the micro-endmills was examined before performing the experiments. Twenty endmills specially ordered from the same production batch were examined under an optical microscope in order to study the edge radius at the endmill tip. Photos were taken and then processed with a threshold filter to clearly reveal the edge geometry of the endmill. As expected based on previous measurement work on conventional machining inserts by Schimmel et al. [24], significant variability was observed in the edge radii of the tooling, with estimated radii varying from approximately 1 μm up to approximately 5 μm. Of this batch of 20 tools, five were selected that had edge radii measured to be 2 μm. An additional five endmills were selected that had the edge radii measured to be approximately 5 μm. The processed images of endmills with small and large edge radii are shown in Fig. 2. The endmills were checked after machining the slots, and the change in tool geometry was found to be negligible.

2.2 Experiment Setup. Due to process-specific limitations of conventional machine tools, a miniature machine tool testbed has been developed to perform micromilling experimentation [25,26]. This testbed contains a 150,000 rpm, air-turbine spindle with a 3.175 mm dia chuck to accept commercially available tooling. The high rotational velocities of this spindle are required to achieve recommended cutting velocities for good process performance for the machining of most steel and irons (100–500 m/min) with miniature endmills of diameters less than 1 mm. For example, Spath and Huntrup [20] found that the surface roughness of micromilled steel workpieces improved as the cutting velocity was increased from 100 to 285 m/min. The runout of this spindle was estimated by observing force peaks to be less than 1 μm. The testbed contains three voice-coil-actuated axes capable of 25, 20, and 25 mm of travel in x, y, and z directions, respectively, with 1 μm resolution linear encoders used to provide positioning feedback. M3 tapped holes are located on the y-axis stage to allow for part fixturing.

A Kistler 9018 triaxial load cell is mounted onto the y-axis, as shown in Fig. 3. This load cell has a force measurement threshold of 20 mN. A Kistler 8694M1 triaxial accelerometer with a bandwidth of 20 kHz was mounted on the workpiece to provide additional sensing capabilities. Force data sampled at 40 kHz will be analyzed in Part II of this paper [27].
2.3 Surface Roughness Measurement. After the slots were machined, the surface heights were measured with a Wyko NT 1000 optical profiler. With a 5× optical lens, a 1.2 mm by 0.9 mm area was sampled with 1.6 and 2.8 μm resolution in the feed and normal-to-feed directions, respectively, and sub nanometer resolution in the vertical direction. This measurement results in a two-dimensional (2D) grid of surface heights from which a line will be sampled along the slot centerline to obtain the \( R_a \) value.

To study the effect of workpiece microstructure on the surface generation mechanism, it is desired to obtain a measurement trace containing enough grains to provide for the broad statistical distribution of the grains in the microstructure. The average grain sizes of the workpiece microstructures are 70, 20, 70, and 50 μm for the ferrite, pearlite, pearlitic ductile iron, and ferritic ductile iron, respectively. For the ductile iron microstructures considered in this paper, a measurement length of approximately 2.5 mm is required to obtain a trace with 20 ferrite-pearlite grain pairs of roughly 120 μm in length on average. Since a single measurement area is smaller than the 2.5 mm length desired, multiple measurement sets were collected as shown in Fig. 4 and then combined to provide complete coverage of the machined slot. As shown in Fig. 4(a), the measurement area of the first set is bounded by the dashed line, while the measurement area of the adjacent set is bounded by the dotted line. The measurements were made so that there was an overlap of about 200 μm between two adjacent data sets to facilitate the alignment of the adjacent measurement sets. The five data sets were then combined into one larger set in order to provide data for the entire slot.

The following two-step procedure was repeatedly implemented to combine the five measurement sets into one set that covers the entire cut. First, for two adjacent and partially overlapping measurement sets, the shifts in \( x \) and \( y \) that result in the minimal mean-squared error difference between the measurement values for the overlapping regions are determined. Second, the rotations about the \( x \)-axis and \( y \)-axis and the translation along the \( z \)-axis are determined in the same manner. Once two measurement sets are combined, the same procedure can be used to overlay this combined measurement set and the third measurement set. This procedure is repeated until all five sets are combined.

2.4 Surface Roughness Experimental Results. The arithmetic surface roughness \( R_a \) for each test condition is found by selecting a line of measurement points approximately 2.5 mm long along the center of the slot in the 5 mm by 0.9 mm combined measurement set of the overall slot as shown in Fig. 4. The centerline of the slot was found by selecting the row of surface heights from the measurement grid that is closest to the midpoint between the slot sidewalls. The line of points was then processed with a 200 μm cutoff to eliminate longer wavelength components from the surface analysis.

The computed \( R_a \) values are listed in Table 2. The \( R_a \) values vary from 0.07 μm for a pearlite sample to 0.30 μm for a pearlitic ductile iron sample. The \( R_a \) values for each material [Ferrite (F), Pearlite (P), Ferritic Ductile Iron (FDI), and Pearlitic Ductile Iron (PDI)] and feed rate combination are shown in Fig. 5 for the 2 μm edge radius and 50 μm depth of cut conditions. The two single-phase materials, ferrite and pearlite, have micromilled surfaces.

### Table 2 Surface roughness values, \( R_a \) (μm)

<table>
<thead>
<tr>
<th>Material</th>
<th>2 μm edge radius</th>
<th>5 μm edge radius</th>
<th>2 μm edge radius</th>
<th>5 μm edge radius</th>
<th>2 μm edge radius</th>
<th>5 μm edge radius</th>
<th>2 μm edge radius</th>
<th>5 μm edge radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial DOC (μm) Feedrate (μm/Flute)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.25</td>
<td>0.11</td>
<td>0.15</td>
<td>0.12</td>
<td>0.16</td>
<td>0.15</td>
<td>0.18</td>
<td>0.17</td>
</tr>
<tr>
<td>0.5</td>
<td>0.09</td>
<td>0.15</td>
<td>0.13</td>
<td>0.10</td>
<td>0.15</td>
<td>0.15</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>2</td>
<td>0.09</td>
<td>0.12</td>
<td>0.13</td>
<td>0.15</td>
<td>0.17</td>
<td>0.21</td>
<td>0.21</td>
<td>0.22</td>
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<tr>
<td>3</td>
<td>0.09</td>
<td>0.10</td>
<td>0.10</td>
<td>0.14</td>
<td>0.17</td>
<td>0.25</td>
<td>0.24</td>
<td>0.25</td>
</tr>
<tr>
<td>0.25</td>
<td>0.12</td>
<td>0.15</td>
<td>0.17</td>
<td>0.23</td>
<td>0.15</td>
<td>0.25</td>
<td>0.21</td>
<td>0.20</td>
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<tr>
<td>0.5</td>
<td>0.12</td>
<td>0.14</td>
<td>0.13</td>
<td>0.20</td>
<td>0.17</td>
<td>0.20</td>
<td>0.20</td>
<td>0.24</td>
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<tr>
<td>100</td>
<td>1</td>
<td>0.09</td>
<td>0.14</td>
<td>0.18</td>
<td>0.25</td>
<td>0.21</td>
<td>0.20</td>
<td>0.24</td>
</tr>
<tr>
<td>2</td>
<td>0.07</td>
<td>0.09</td>
<td>0.14</td>
<td>0.18</td>
<td>0.25</td>
<td>0.21</td>
<td>0.21</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>0.08</td>
<td>0.09</td>
<td>0.09</td>
<td>0.13</td>
<td>0.22</td>
<td>0.26</td>
<td>0.21</td>
<td>0.24</td>
</tr>
</tbody>
</table>
that are smoother than the multiphase ductile irons, and the trend with increasing feed rate is different between the single-phase and multiphase materials. Additionally, neither the single-phase materials nor the multiphase materials follow the trend normally observed based on tool corner radius, $R$, and the feedrate, $f$.

$$R_a = \frac{f^2}{R} \tag{1}$$

### 3 Modeling and Analysis of Surface Generation for Single-Phase Materials

In this section, the surface generation behavior for the single-phase ferrite and pearlite materials is explained in light of the minimum chip thickness concept. First, the need for this enhanced surface generation model in micromilling will be explained based on the experiment results of the single-phase materials. A model will then be presented that uses the minimum chip thickness values for the materials to predict the surface profile along the centerline of a slot using the endmill geometry. Then, the FE simulation approach undertaken in this work to determine the minimum chip thickness for ferrite and pearlite will be presented. Finally, this surface generation model will be validated.

#### 3.1 Motivation for Surface Generation Model

In order to investigate the effects of the micromilling process conditions on the surface generation mechanism for single-phase materials, the $R_a$ value results for the variable levels in Table 3 were used to compute the effect estimates of a $2^4$ full factorial experimental design [28]. For the single-phase analysis, three main effects are found to be significant. The significant experiment effects for the $R_a$ surface roughness response were computed to be 0.031, 0.034, and $-0.049 \mu m$ for the material, tool condition, and feed rate variables, respectively. These results indicate that slots micromilled in ferrite result in a rougher surface than slots produced in pearlite. Slots produced with a 5 $\mu m$ edge-radiused tool are also found to have a rougher surface than those made with a 2 $\mu m$ edge-radiused tool. Feed rate is found to have a negative effect on the surface roughness, indicating that surfaces produced with the higher feed rate value (3.0 $\mu m$/flute) have a smoother surface than those produced with the lower feedrate value (0.25 $\mu m$/flute). The feed rate result is similar to that observed by Weule et al. [14] in their steel microcutting experiments and the trend observed by Kim et al. [12] in their micromilling of brass. The axial depth of cut was found to have no effect on the surface roughness of the slot floor over the range studied.

The effects of material, feed rate, and cutting edge radius can all be explained by the concept of the minimum chip thickness [11]. The minimum chip thickness concept states that the workpiece material will not be cut if the uncut chip thickness is less than a certain value (the minimum chip thickness) and that the uncut workpiece surface will deform elastically beneath the cutting edge and then recover to very near the original surface height. This value has been found to be a fraction of the cutting edge radius of the tool and has been shown to be material-property dependent, with more ductile materials exhibiting a higher minimum chip thickness [11,14].

#### 3.2 Surface Generation Model Development

A model to predict the surface generated using the minimum chip thickness concept and the more complex endmilling geometry is now presented. The model generates the surface profile produced along the centerline of the slot. For each tool pass, the surface profile is computed as the combination of the previously computed surface profile and that segment of the tool profile for which the minimum chip thickness is exceeded. The following procedure is used to develop the surface profile prediction. First, the tool profile $y_{t0}$ is determined by considering the corner radius of the tool and the end cutting edge angle as shown in Fig. 6(a).

$$y_{t0}(x) = \left\{ \begin{array}{lr} \frac{-\sqrt{r_c^2-x^2}}{r_c} & x > -r_c \sin(ECEA) \\ -r_c \cos(ECEA) - [x + r_c \sin(ECEA)] \tan(ECEA) & x \leq -r_c \sin(ECEA) \end{array} \right. \tag{2}$$

Then, the line representing the minimum chip thickness is found by creating a line offset to the tool profile, $y_{t0}$ at a distance of $t_{c,min}$ along the normal direction $n$ for each point along the tool profile,

$$y_{t_{c,\text{min}}}(x) = y_{t0}(x) + n(x) \cdot t_{c,\text{min}} \tag{4}$$

as shown in Fig. 6(b).

The surface profile may now be generated in the following incremental manner. The surface profile is initially assumed to have the tool geometry profile of Eq. (2). For each subsequent tool...
pass, the tool profile and the minimum chip thickness offset line are shifted a distance equal to the feed per flute. Figure 6(c) shows the case for the first tool pass. The initial surface profile is assumed to be equal to \( y_{t0} \). Then, the surface profile is modified by considering each point along the next tool profile \( y_{t1} \), in Fig. 6(c), and the loci of minimum chip thickness locations for that tool pass \( y_{tC, min} \). For each point along the tool profile at which the corresponding minimum chip thickness location is to the left of the generated surface, the surface profile is updated to include that point on the tool profile. For example, in Fig. 6(c), at point A along the tool profile, the corresponding minimum chip thickness point \( A' \) is to the right of the generated surface. Therefore, there is no chip formation at point A and the surface is not updated to include point A. However, at point B, the corresponding minimum chip thickness point \( B' \) is to the left of the generated surface, indicating that the chip thickness at point B is large enough to remove a chip. Thus, the generated surface is updated to include point B. This process is then repeated to build a representative surface profile as shown in Figs. 6(d) and 6(e) for the surface profile with and without the tool edge locations, respectively. Once the surface profile is generated, the arithmetic mean value \( R_a \) is computed.

### 3.3 FE Simulation for Minimum Chip Thickness Determination

In order to use the enhanced surface generation model, the minimum chip thickness \( t_{C, min} \) in Eq. (4) needs to be determined. In the past, researchers have often had to resort to tedious experimentation or small-scale molecular dynamics simulations to estimate the minimum chip thickness. Weule et al. [14] and Kim et al. [12] observed the minimum chip thickness experimentally. Shimada et al. [11] used molecular dynamics simulations to determine the minimum chip thickness for edge radii commonly produced on diamond inserts. They found that the minimum chip thickness could be as small as 0.05 times the edge radius for the machining of copper.

In this study, the FE simulation tool developed by Chuzhoy et al. [21] to study the influence of workpiece microstructure on macromilling chip formation was used to determine the minimum chip thickness for the single-phase ferrite and pearlite phases at length scales representative of micromilling. Specially prepared, pure ferrite and pearlite samples were produced, and material characterization experiments were performed by Chuzhoy et al. [22] to determine the parameters of the Bammann-Chiesa-Johnson (BCJ) state variable plasticity model [29] for each phase individually.

The minimum chip thickness was determined for both the ferrite and pearlite phases by simulating the orthogonal machining process with the conditions listed in Table 4. An identical 24 \( \mu m \) by 15 \( \mu m \) mesh with an initial average mesh size of 0.5 \( \mu m \) was used for each simulation. The results of each simulation were studied to determine if the workpiece surface behind the tool was at the same height as the uncut mesh, indicating no new surface generation, or if a new workpiece surface was formed during the simulation. The output of the surfaces created during two FE simulations are shown in Fig. 7. Figure 7(a) shows the simulation for the case of ferrite machining with a 2 \( \mu m \) edge radius and 0.1 \( \mu m \) chip thickness. It is observed that the workpiece surface behind the tool recovers to the identical height as the workpiece surface ahead of the tool. However, in Fig. 7(b), the workpiece

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**Table 4** FE Simulation conditions for minimum chip thickness determination

<table>
<thead>
<tr>
<th>Variable</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edge radius</td>
<td>2 and 7 ( \mu m )</td>
</tr>
<tr>
<td>Rake angle</td>
<td>0 and 7 deg</td>
</tr>
<tr>
<td>Clearance angle</td>
<td>5 and 11 deg</td>
</tr>
<tr>
<td>Chip thickness</td>
<td>0.1, 0.25, 0.5, 1, 2, and 3 ( \mu m )</td>
</tr>
</tbody>
</table>

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**Fig. 7** Screen dump of FE simulation with chip thickness (a) below minimum chip thickness and (b) above minimum chip thickness
surface behind the tool is lower than the original surface for the pearlite simulation with 2 \( \mu \text{m} \) edge radius and 0.5 \( \mu \text{m} \) chip thickness.

By observing the workpiece surface behind the tool, the presence of chip formation was determined for each of the simulations. The chip thickness-to-edge radius ratio was then computed for each of the simulations. The largest chip thickness-to-edge radius ratio that resulted in no new surface being formed is 0.14 for the pearlite simulations, observed during the simulations with 1.0 \( \mu \text{m} \) chip thickness and 7 \( \mu \text{m} \) edge radius. The smallest chip thickness-to-edge radius ratio that resulted in chip formation was 0.25, observed during the simulations with 0.5 \( \mu \text{m} \) chip thickness and 2 \( \mu \text{m} \) edge radius. Therefore, assuming a constant ratio for the minimum chip thickness as the edge radius varies, the minimum chip thickness ratio for pearlite is estimated to lie in the range of 0.14 – 0.25 based on the results of the FE simulations. The value of 0.20 was chosen for the simulations used in the remainder of this paper to represent the minimum chip thickness for pearlite. In a similar manner, the minimum chip thickness ratio for ferrite was determined to be 0.35, a value in the range of minimum chip thickness ratios from 0.29 – 0.43. These two values follow the trend observed by Weule et al. [14] that more ductile materials have a higher minimum chip thickness.

### 3.4 Model Validation

After the determination of the minimum chip thickness ratios from the FE simulations, the model can be employed to predict the surface profile for ferrite and pearlite. The end cutting edge angle and corner radius were determined from measurement of the tooling with an optical microscope to be 10\(^\circ\) and 2 \( \mu \text{m} \) respectively. Minimum chip thickness ratios of 0.20 and 0.35 were used for pearlite and ferrite, respectively, as previously determined. The predicted surfaces for pearlite and ferrite with feed rates of 0.5 and 2.0 \( \mu \text{m} \)/flute are shown in Fig. 8. For the 0.5 \( \mu \text{m} \)/flute feed rate for both ferrite and pearlite, the surface profile contains a sawtooth appearance with a wavelength of 1 \( \mu \text{m} \), not at the feed per flute, due to the minimum chip thickness. For the 2 \( \mu \text{m} \)/flute feedrate, the periodic behavior is observed with a wavelength of 2 \( \mu \text{m} \) that is equal to the feed per flute. Therefore, when the feed rate is reduced from 2.0 to 0.5 \( \mu \text{m} \)/flute, a chip is not formed during every tool pass. This behavior was also observed by Kim et al. [12]. Additionally, the amplitude of the variation is similar for both materials at the 2 \( \mu \text{m} \)/flute feed rate. However, at 0.5 \( \mu \text{m} \)/flute feed rate, the amplitude of the ferrite surface is larger than that for the pearlite, resulting in a larger surface roughness for the ferrite surface.

The surface generation model based on the minimum chip thickness concept accurately predicts both the feed rate trends and the magnitude of the surface roughness for both single-phase materials very well as shown in Figs. 9 and 10 for the ferrite and pearlite, respectively. Figure 11 shows the effect of the minimum chip thickness on the surface roughness. The effect of the minimum chip thickness is dominant at lower values of the feed rate. As the feed rate is increased, the surface roughness approaches the value that would be computed based solely on the geometry of the tool and the process conditions. Without this effect, the surface roughness values would exhibit the conventional trend of increasing roughness with increasing feed rate. The difference between the two curves is the component of the feed rate that is due to the minimum chip thickness effect. This minimum chip thickness component decreases as the feed rate is increased, as seen in the decreasing gaps between the two curves as the feed rate approaches 3 \( \mu \text{m} \)/flute. The addition of the geometric effect of the tool and process conditions and the minimum chip thickness effect produce an optimal feedrate in terms of surface roughness as ob-
served in Fig. 10 for the pearlite surface roughness with a 2 \( \mu m \) edge-radiused tool. This optimal feed rate is a function of the cutting edge radius and the workpiece material properties via the minimum chip thickness, with the optimal feed rate for the tool-workpiece pair increasing as the cutting edge radius and/or material ductility increases. Therefore, this optimum location is expected to be located at a feed rate greater than 3 \( \mu m/\text{flute} \) for the ferrite samples due to its larger minimum chip thickness.

4 Analysis of Surface Generation for Multiphase Materials

In this section, the surface generation phenomena present in the micromilling of multiphase materials is considered. First, the differences in the surface generation process between single-phase and multiphase materials are discussed. Then, the chip-formation process in the micromilling of multiphase materials is investigated to explain the difference in the surface-generation process. Finally, the three phenomena occurring in the surface-generation process for multiphase materials are identified.

4.1 Comparison of Single-Phase and Multiphase Surface Generation. In order to study the effect of the multiphase nature of the workpiece material on the surface generation, the experimental results from the pearlite slots and the pearlitic ductile iron slots are compared in a \( 2^4 \) factorial design using the levels listed previously in Table 3 for the single-phase experimentation, except for the material variable for which pearlite and pearlitic ductile iron are used. From this analysis, the three main and two two-factor interaction effects that are significant are listed in Table 5. The cutting edge radius main effect indicates that, as in the single-phase analysis, a 5 \( \mu m \) edge-radiused tool produces surfaces with a larger surface roughness than those made with a 2 \( \mu m \) edge-radiused tool.

Since the workpiece material and axial depth of cut are found to have significant interaction effects as well as significant main effects, their effect must be considered in conjunction with the other variable in the interaction. Two-way diagrams are shown in Fig. 12 for both two-factor interaction effects. For the material and feed rate interaction, it is observed that for the pearlite workpiece slots, increasing the feed rate from 0.25 to 3.0 \( \mu m/\text{flute} \) results in a smoother workpiece surface, however, for pearlitic ductile iron, increasing the feed rate results in the opposite trend, a rougher surface. The two-way diagram for material and axial depth of cut shows that changes in the axial depth of cut have no effect on the pearlite slots, but that increasing the axial depth of cut results in a rougher slot floor surface for the pearlitic ductile iron workpiece. These two-factor interactions indicate that the surface generation behavior is different for multiphase workpiece materials than for single-phase workpiece materials.

Based on the results of the \( 2^4 \) factorial analysis performed earlier, it is observed that the surface roughness of the multiphase ductile iron slots cannot be fully explained by using the minimum chip thickness concept as was the case for the ferrite and pearlite data. Predictions for the ferritic ductile iron were determined by using a weighted average of the surface roughness values from the model for the ferrite and pearlite materials. These predictions are shown in Fig. 13 along with the experimental values. Clearly,
neither the magnitude nor the feed rate trend is accurately predicted by this approach.

4.2 Chip Formation Mechanism in Multiphase Materials

Due to the mismatch in the surface predictions for the multiphase materials, the surface was analyzed in more detail to determine the nature of the difference. In order to investigate the role of the microstructure, the frequency spectrum of the surface trace is also considered to determine the influence of the workpiece microstructure on the surface generation process. The surface spectra for all four materials are shown in Fig. 14 for the feed rate of 0.5 \( \mu \text{m} \), the axial depth of cut of 50 \( \mu \text{m} \), and the 2 \( \mu \text{m} \) edge radius tool. As noted previously, the sample resolution of the surface measurements is 1.6 \( \mu \text{m} \) in the feed direction, which is not small enough to observe spectral components at the feed rates. However, based on the work of Kim et al. [12], it is not expected to find spectral components at the value of the feed rate due to the minimum chip thickness.

For the ferrite and pearlite spectra, the power spectra are relatively flat and much lower in magnitude than the ductile iron surface spectra. For the ductile iron samples, there are significant energies in the spectra around wavelengths of 50 and 70 \( \mu \text{m} \) for the ferritic and pearlitic ductile irons, respectively. The peaks of the spectra are found to be located at wavelengths of 55 and 67 \( \mu \text{m} \). These wavelengths are the near average phase spacing in the ductile iron materials. There is significant energy at a band of wavelengths between 40 and 100 \( \mu \text{m} \), and between 40 and 130 \( \mu \text{m} \) for the ferritic and pearlitic ductile irons, respectively. This variation in the spectra further indicates that the phenomenon is phase boundary dependent and not a vibration resonance phenomenon. A vibration resonance phenomenon would be exhibited as a sharp peak at one frequency, whereas a phase boundary is expected to have a wider frequency response for two reasons. First, the grains naturally have a rather broad distribution of sizes. Second, in addition to the size distribution, the slot floor is a two-dimensional slice of the three-dimensional microstructure further contributing to a wider range of individual phase segments along the cutter path. Therefore, both the peak wavelength and the wide band in the surface spectra indicate that a significant portion of the surface roughness is due to phase boundary effects.

To further study the role of phase boundaries, the slot floor was also examined with a scanning electron microscope (SEM) as shown in Fig. 15. For the (a) pearlite and (b) ferrite slot floor images, the surface appears relatively smooth with no indication of any grain-size effects. The average grain size of the pearlite and ferrite are 20 and 100 \( \mu \text{m} \), respectively [30]. Note that the magnification of the pearlite image is higher than for the other images to show the absence of phenomena occurring at the grain boundaries. However, for the (c) ferritic ductile iron and the (d) pearlitic ductile iron, there is clearly something present on the surface at distances correlating to the band of wavelengths representative of the grain spacing, roughly between 40 and 120 \( \mu \text{m} \). Higher magnification inspection of the surface revealed that the lighter colored regions are miniature “burrs” that have formed at distances that are comparable to the spacing between grain boundaries for both ductile iron materials, while the ferrite and pearlite surfaces appear smooth. One possible explanation for this behavior at the phase boundaries is that the chip-formation process is not continuous as the cutting edge moves from one phase to another. As the cutting edge moves between phases, the chip-formation process becomes interrupted as the tool exits a phase at the grain boundary and a burr forms at the phase boundary.

To obtain some evidence to test this hypothesis, chips were collected from the machining of the four materials and examined with a SEM as shown in Fig. 16. While the (a) pearlite and (b) ferrite chips appear more continuous, the (c) ferritic ductile iron and (d) pearlitic ductile iron chips are highly fragmented, indicating the discontinuous and/or interrupted nature of the chip-formation process. Based on the size of the ferrite and pearlite chips, they appear to have been formed during one complete tool pass. The ductile iron chips, however, are much smaller than would be expected for a complete tool pass, indicating that they were formed during a fraction of a tool pass. Therefore, there is some evidence that the chip-formation process becomes interrupted when machining across phase boundaries of multiphase materials, leading to the formation of miniature burrs on the workpiece surface.

The formation of burrs at the grain boundaries increases the surface roughness of the material when the surface is measured over multiple phases in the material. These burrs create frequency components in the surface height data that are related to the spacing between the burrs, in this case, peaking near the average phase spacing of 50 and 70 \( \mu \text{m} \) for the ferritic and pearlitic ductile irons, respectively, and spread over a range of wavelengths from 40 to 130 \( \mu \text{m} \), as shown in Figs. 14(a)–14(d).
4.3 Surface Generation Phenomena for Multiphase Materials. The above analysis of the chip formation process during micromilling of multiphase materials suggests that the surface generation process for multiphase workpiece materials is more complex than that for single-phase materials. This is not to say that the minimum chip thickness concept is not at work for multiphase materials, but rather that an additional mechanism, burr formation at the grain boundaries, is also present. One might theorize from the appearance of Fig. 13 that this burr formation phenomenon increases the roughness with increasing feedrate while the minimum chip thickness phenomenon decreases roughness with increasing feedrate. To demonstrate this interpretation, Fig. 17 shows the smaller edge radius, ferritic ductile iron data decomposed into two effects. The lowest line is the \( R_a \) prediction based solely on the corner radius and end cutting edge angle of the tool. The dashed line is the predictions from the minimum chip thickness model, which includes both the geometric effect and the effect of the minimum chip thickness effect. Finally, the experimental data are plotted. The effect of the minimum chip thickness is characterized as the difference between the model prediction and the lowest line. Therefore, the effect of the minimum chip thickness is predominately occurring at the lower feed rates. The effect of the burr formation on the surface roughness for multiphase materials can be approximated as the difference between the model predictions and the experiment data. This effect appears to increase as the feed rate is increased. Larger feed rates result in larger chip thicknesses that lead to more pronounced burr formation. For feed rates above approximately 1 \( \mu m/\text{flute} \), the surface roughness for multiphase materials is influenced more by the effect of the burr formation than by the minimum chip thickness effect. Below 1 \( \mu m/\text{flute} \), both the effects of the minimum chip thickness and of burr formation appear to be roughly equal in magnitude in their influence on the surface roughness of multiphase materials.

5 Conclusions

In summary, as the endmilling process is miniaturized, scaling laws affect the surface generation process in several ways. For single-phase materials, the edge radius of the cutting tool plays an important role in the surface generation process through the minimum chip thickness. For multiphase materials, the process can be more accurately considered to consist of a series of single-grain or -phase machining operations rather than the machining of some homogeneous material. The larger the difference between the machining characteristics of the different grains or phases, the more likely is the presence of interrupted chip formation, leading to rougher surfaces. Thus, in micromilling of multiphase materials, the proper selection of workpiece material and its appropriate microstructure are very important in realizing the full potential of the endmilling process at the submillimeter scale.

Based on the micromilling experimentation and modeling efforts presented in this paper, the following conclusions can be drawn:

1. The surface roughness \( R_a \) values at the bottom of slots produced in single-phase ferrite and pearlite do not monotonically increase as feed rate is increased, as is generally the case in conventional machining operations. This effect has been explained by the minimum chip thickness concept.
2. Over the range of values considered, (50–100 \( \mu m \)) the axial depth of cut was not found to have a significant effect on the \( R_a \) values for single-phase materials, suggesting that the productivity of the micromilling process may be increased without sacrificing the surface roughness of the slot floor.
3. Orthogonal machining FE simulations at the microstructure level were employed to determine the minimum chip thickness values. The minimum chip thickness value for ferrite is greater than that for pearlite, following the observations by other researchers that the minimum chip thickness is larger for more ductile materials.
4. A model has been developed to predict the surface generation for single-phase materials based on the minimum chip thickness concept. The magnitude and trend in the \( R_a \) values for single-phase micromilling experimentation are predicted well by this model. For single-phase materials, the data and model predictions indicate that an optimal feed rate exists that will produce the smallest \( R_a \) value. This optimal feed rate exists due to the tradeoff between the traditional effect of feedmarks as the feed rate is increased and the minimum chip thickness effect resulting in tool passes that do not remove any material as the feed rate is reduced.
5. The \( R_a \) values for the slots micromilled in multiphase ductile iron workpieces are larger than the \( R_a \) values from the slots produced in the two main constituents of ductile iron: ferrite and pearlite. Spectra of the floor surface height indicate that large components of the surface roughness can be found at wavelengths corresponding to the phase boundaries. SEM images of the floor surface indicate burrs formed at phase boundaries.
6. SEM images of chips from the micromilling process indicate that the chip-formation process is different between single-
phase and multiphase materials. The chip-formation process is interrupted when machining the multiphase ductile iron materials, reinforcing the hypothesis that burrs are found at grain boundaries that contribute to increased surface roughness for the micromilling of multiphase materials.

7. For multiphase materials, the surface roughness is shown to be a combination of three separate effects: a geometric effect, a minimum chip thickness effect, and a burr formation at the grain boundaries effect.

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