http://www.doi.org/10.62341/istj-vol39-1-ar23

Received	**2026/07/12**	**تم استلام الورقة العلمية في**
Accepted	**2026/08/02**	**تم قبول الورقة العلمية في**
Published	**2026/08/04**	**تم نشر الورقة العلمية في**

A Hybrid 2D–3D Framework for Efficient and Accurate Grinding Process Simulation

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Abstract:

Grinding is considered one of the most complex manufacturing processes due to the stochastic nature of wheel topography and the interactions between abrasive grains and the workpiece. Therefore, accurate simulation plays a critical role in defining uncut chip thickness and contact length, as well as predicting surface quality and optimizing process parameters. In this study, a comparative analysis is presented between two-dimensional (2D) and three-dimensional (3D) grinding simulation frameworks based on the Z-map technique. The models were developed using data from a foundational study on grinding wheel topography, enabling a consistent evaluation of both approaches in terms of computational efficiency and accuracy.

The results show that 2D models can provide a high level of accuracy in simulations with constant parameters, with deviations not exceeding 0.25% compared to 3D results. However, in stochastic simulations, the 2D approach tends to underestimate key parameters such as uncut chip thickness (by up to 60.3%) and contact length (by approximately 19.7%). This limitation is mainly attributed to the inability of 2D models to capture off-center grain interactions. On the other hand, despite their high computational cost—requiring up to 4–5 days on a single-core system—3D simulations provide a more realistic representation of the grinding process. The results show strong agreement with experimental measurements of surface roughness (Ra = 2.1 µm compared to 1.9 µm experimentally).

Recent developments between 2016 and 2026, particularly in parallel computing and active-point selection techniques, have significantly improved the efficiency of 3D simulations. These advancements help reduce the gap between the efficiency of 2D models and the accuracy of 3D approaches, paving the way toward real-time, high-fidelity kinematic simulations. To overcome the limitations of full 3D modeling, a hybrid 2D–3D simulation framework is proposed. This approach combines the efficiency of 2D models with the accuracy of 3D simulations, reducing computational time from several days to a few hours while maintaining a high level of predictive accuracy.

Keywords: Grinding simulation, Hybrid 2D–3D modeling, Z-map technique, Uncut chip thickness, Surface roughness, Grinding wheel topography.

محاكاة لعملية التجليخ في اطار هجيني ثنائي وثلاثي الأبعاد لتحقيق الدقة والكفاءة

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الملخص تُعدّ عملية التجليخ من أكثر عمليات التصـنيع تعقيدًا نظرًا لطبيعة شكل عجلة التجليخ العشـــوائية والتفاعلات بين حبيبات الكشــط وقطعة العمل. لذا، تلعب المحاكاة الدقيقة دورًا حاسـمًا في تحديد سُـمك الرايش غير المقطوع وطول التلامس، فضــلًا عن التنبؤ بجودة السطح وتحسين معايير العملية. تُقدّم هذه الدراسة تحليلًا مقارنًا بين إطارَي محاكاة التجليخ ثنائي وثلاثي الأبعاد، اســـتنادًا إلى تقنية خريطة Z. طُوّرت النماذج باستخدام بيانات من دراسة أساسية حول تضاريس عجلة التجليخ، مما يُتيح تقييمًا متسقًا

لكلا النهجين من حيث الكفاءة الحسـابية والدقة. تُظهر النتائج أن النماذج ثنائية الأبعاد تُوفّر مستوى عالٍ من الدقة في عمليات المحاكاة ذات المعايير الثابتة، حيث لا تتجاوز الانحرافات 0.25% مقارنةً بنتائج النماذج ثلاثية الأبعاد. مع ذلك، في عمليات المحاكاة العشوائية، يميل النهج ثنائي الأبعاد إلى التقليل من تقدير المعايير الرئيسية مثل سُمك الرايش غير المقطوع (بنسبة تصل إلى 60.3%) وطول التلامس (بنسبة 19.7% تقريبًا). يُعزى هذا القصور بشكل رئيسي إلى عدم قدرة النماذج ثنائية الأبعاد على رصد تفاعلات الحبيبات غير المركزية. من جهة أخرى، ورغم تكلفتها الحسابية العالية – التي قد تصل إلى 4–5 أيام على نظام أحادي النواة – توفر عمليات المحاكاة ثلاثية الأبعاد تمثيلاً أكثر واقعية لعملية التجليخ. وتُظهر النتائج توافقًا كبيرًا مع القياسات التجريبية لخشونة السطح ($Ra = 2.1\mu m$ مقارنةً بـ $1.9\mu m$ تجريبيًا).وقد ساهمت التطورات الحديثة بين عامي 2016 و2026، ولا سيما في مجال الحوسبة المتوازية وتقنيات اختيار النقاط النشطة، في تحسين كفاءة عمليات المحاكاة ثلاثية الأبعاد بشكل ملحوظ. وتُساعد هذه التطورات في تقليص الفجوة بين كفاءة النماذج ثنائية الأبعاد ودقة الأساليب ثلاثية الأبعاد، مما يمهد الطريق نحو عمليات محاكاة حركية عالية الدقة في الوقت الفعلي. وللتغلب على قيود النمذجة ثلاثية الأبعاد الكاملة، يُقترح إطار عمل هجين للمحاكاة ثنائية وثلاثية الأبعاد. يجمع هذا النهج بين كفاءة النماذج ثنائية الأبعاد ودقة عمليات المحاكاة ثلاثية الأبعاد، مما يقلل وقت الحساب من عدة أيام إلى بضع ساعات مع الحفاظ على مستوى عالٍ من دقة التنبؤ.

الكلمات المفتاحية: محاكاة التجليخ، النمذجة الهجينة ثنائية وثلاثية الأبعاد، تقنية خريطة Z، سمك الرقاقة غير المقطوعة، خشونة السطح، تضاريس عجلة الطحن.

1- Introduction

Grinding continues to play a vital role in the manufacturing of high-precision components, where both surface integrity and dimensional accuracy are of primary importance. However, the stochastic distribution of abrasive grains on the grinding wheel surface makes the process inherently difficult to model with high fidelity.

Traditionally, two-dimensional (2D) simulations have been widely used to simplify the complex three-dimensional interactions between the grinding wheel and the workpiece. In these approaches, the process is typically represented as a sequence of planar cuts, which significantly reduces computational cost. However, with the increasing demand for improved surface quality and more accurate process optimization, the limitations of these simplified models have become increasingly evident.

To overcome these limitations, three-dimensional (3D) simulation frameworks have been developed to capture the full volumetric interactions of abrasive grains. These models account for important factors such as grain spatial distribution, variations in protrusion height, and overlapping cutting paths, which collectively define the final surface topography. As a result, 3D simulations provide a more realistic representation of the grinding process.

In addition to improved predictive capability, 3D models enable the integration of physically significant processes that directly influence grinding performance. One such process is grinding wheel dressing, which plays a crucial role in conditioning the wheel surface and controlling its cutting behavior. Previous work by Darafon et al. [1]. introduced a novel simulation of the dressing operation using a single-point diamond tool within a 3D grinding framework. The results demonstrated that dressing significantly alters grain geometry and surface topography, leading to strong agreement between simulated and experimental results. Such process-level modeling cannot be adequately captured using simplified 2D approaches.

Despite these advantages, full 3D simulations are associated with high computational cost, which limits their applicability in large-scale simulations and parametric studies.

To address this challenge, hybrid 2D–3D simulation approaches have recently emerged as a promising solution. These methods aim to combine the computational efficiency of 2D models with the predictive accuracy of 3D simulations by decomposing the problem into multiple simplified sub-domains while preserving essential three-dimensional interactions.

In this context, the present study provides a systematic comparison between 2D, 3D, and hybrid simulation frameworks, with particular emphasis on their ability to predict key process parameters, including uncut chip thickness, contact length, and surface roughness. By utilizing detailed data from the foundational work of Darafon (2013) [2], and positioning it within the context of recent developments (2016–2026), this work aims to clarify the trade-offs between model dimensionality, predictive accuracy, and computational efficiency in modern grinding research.

2- Literature Review

2-1 Evolution of Grinding Topography Models

Early studies on grinding wheel topography primarily relied on statistical descriptions of abrasive grain density and protrusion heights. With time, the focus gradually shifted toward more physically representative approaches. A key development in this transition was the adoption of kinematic simulation techniques, particularly the Z-map method, which was originally introduced for NC tool path verification.

In this approach, the workpiece is discretized into a grid of vertical line segments, enabling efficient computation of material removal through the intersection of tool geometry with these segments [2]. This representation laid the foundation for many subsequent grinding simulation models.

2.2 Recent Advancements (2016–2026)

Over the past decade, research in grinding simulation has increasingly focused on achieving higher agreement with experimental observations while maintaining reasonable computational costs. Two-dimensional (2D) models continue to be widely used as efficient platforms for evaluating material parameters and conducting mesh sensitivity analyses [3].

http://www.doi.org/10.62341/istj-vol39-1-ar23

At the same time, significant progress has been made in enhancing three-dimensional (3D) simulation frameworks through several key approaches:

- **Active-Point Selection:** McDonald et al. (2017) [4] demonstrated that by identifying and simulating only the active cutting points within a measured 3D wheel topography, computational time can be drastically reduced. Their results showed a reduction in runtime from 12 hours to only 4 seconds, while maintaining accurate surface predictions.
- **Deterministic and Stochastic Modeling:** More recent studies have explored both stochastic and deterministic representations of grinding processes. For instance, Zhang et al. (2024) [5] employed stochastic random-plane CBN models to predict 3D workpiece morphology, achieving surface roughness deviations as low as 2.3%. Similarly, Wang et al. (2021) [6] utilized deterministic reconstructions for arrayed diamond wheels, demonstrating good agreement when machining complex alloys such as GH4169.
- **Reduced-Order Models:** Payrebrune et al. (2017) [7] proposed reduced-order 3D models of wheel topography that retain essential dynamical correlations while significantly lowering computational cost compared to full-scale simulations.

Despite these advancements, several challenges remain. In particular, scaling single-grit models to full-wheel industrial simulations, as well as incorporating multi-physics effects such as thermal influences and vibration, continues to represent a significant research gap [3].

In addition, a growing research trend has focused on balancing the trade-off between computational efficiency and simulation accuracy. While 2D models offer fast computation and 3D models provide high fidelity, few studies have attempted to combine the advantages of both approaches within a unified framework. This has led to increasing interest in hybrid modeling strategies, where simplified representations are used in conjunction with high-fidelity simulations to reduce computational cost while preserving essential physical interactions. However, such approaches remain limited and are not yet fully explored in the context of grinding simulation.

3- Methodology

The simulation frameworks investigated in this study are based on the modified Z-map technique for modeling metal removal [8]. Figure 1 illustrates the fundamental differences between the 2D and 3D simulation approaches. In the 2D model, the grinding process is represented along a single plane using line segments, whereas the 3D model captures the full volumetric interaction between abrasive grains and the workpiece.

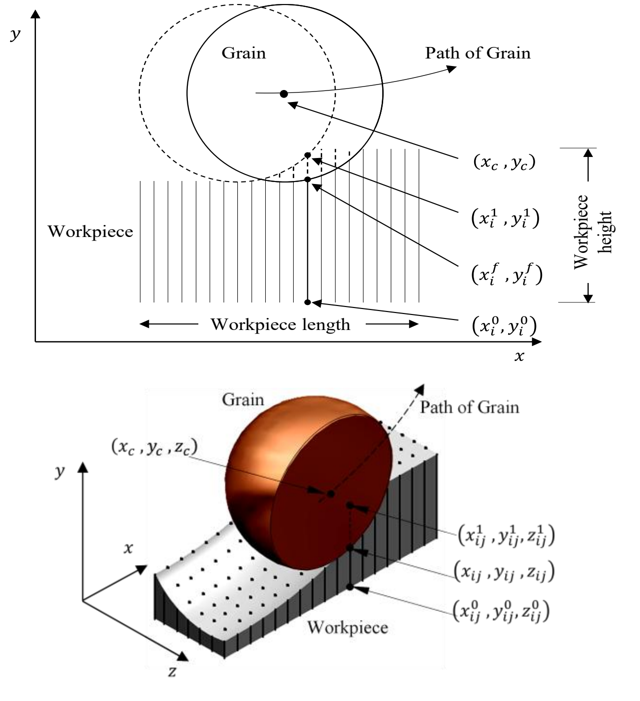

Fig. 1: Schematic representation of 2D and 3D grinding simulation models.

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3-1 2D Simulation Framework

In the 2D framework, the workpiece is represented by a set of evenly spaced vertical line segments along the cutting direction. The formulation is based on the following key assumptions:

- **Workpiece Representation:** The workpiece is discretized into vertical line segments, where the spacing between segments determines the resolution of the model. This spacing is defined by the line segment density (σ_{ls}). An optimal density of $1000\ lines/mm$ (equivalent to $1\ \mu m$ spacing) was selected as a compromise between computational efficiency and accuracy [2].

- **Grain Geometry:** Abrasive grains are assumed to be spherical. In the 2D representation, this assumption reduces to circular geometries. The motion of each grain follows a trochoidal path, resulting from the combination of wheel rotation and linear feed motion [2].

- **Material Removal Logic:** The simulation is performed using discrete time steps (Δt). At each step, material removal is determined by evaluating the intersection between the circular grain profile and the line segments representing the workpiece. Any portion of a segment located within the grain boundary is removed by updating the segment length accordingly. A time step factor of ($dtf\ =\ 1$) was found to provide stable and accurate results [2].

3-2 3D Simulation Framework

The 3D model extends the 2D formulation into a volumetric domain, enabling a more realistic representation of the grinding process. The grinding wheel is generated based on wheel marking system data.

- **Workpiece Representation:** The workpiece is discretized as a grid of vertical line segments distributed over the $x - z$ plane. The

http://www.doi.org/10.62341/istj-vol39-1-ar23

length of each segment (along the y-direction) represents the local workpiece height, while the distribution of segments in the x and z directions defines the workpiece dimensions [2].

● **Metal Removal:** Material removal is computed by evaluating the intersection between spherical abrasive grains and the 3D grid of line segments. Segments intersecting with the grain volume are shortened accordingly, mimicking the physical removal process [2].

● **Parallelization Strategy:** Due to the high computational cost of full 3D simulations (which may exceed five days on a standard desktop system), a parallel computing strategy was implemented. The domain is decomposed into multiple thin sections, each treated as independent 2D slices and executed on separate CPUs within a high-performance computing cluster (ACEnet). This approach reduces the total simulation time from one to two hours, depending on the parameters of the metal removal process [2].

In addition to modeling the grinding process, the 3D simulation framework is capable of incorporating additional physical processes that directly influence wheel topography. One such process is grinding wheel dressing, which plays a critical role in conditioning the wheel surface and determining cutting performance.

Previous work has demonstrated the successful integration of a dressing model within a 3D grinding simulation framework, where the interaction between a single-point diamond tool and abrasive grains was explicitly modeled. The results showed that dressing significantly modifies grain geometry, cutting edge distribution, and the resulting surface topography, with a direct impact on chip formation behavior [1,2].

Although the present study focuses on grinding simulation, the proposed 3D and hybrid frameworks are fully compatible with such dressing models, enabling more comprehensive and physically representative process simulations when required.

http://www.doi.org/10.62341/istj-vol39-1-ar23

3-3 Simulation Parameters

Both simulation frameworks were evaluated under two distinct conditions:

1- Constant Model: All abrasive grains are assumed to have identical size, spacing, and protrusion height.
2- Stochastic Model: Grain sizes, spatial distribution, and protrusion heights are randomized to better represent real grinding wheel topography [2].

3-4 Hybrid 2D–3D Simulation Framework

A major limitation encountered during the development of the full 3D model was the excessive computational cost. A single simulation could require more than five days on a conventional desktop system, making iterative development, debugging, and parametric studies impractical. To address this issue, a hybrid 2D–3D simulation framework was developed. The core concept is to decompose the 3D grinding domain into a series of closely spaced 2D cross-sectional slices. In this approach, a thin section of the grinding wheel–workpiece interaction, with a thickness of 2 mm, is considered. This section is discretized along the x-direction into slices spaced at 1 µm, resulting in approximately 2000 independent 2D models. Each slice is simulated independently using the 2D framework, and the computations are executed in parallel across multiple processing units. This significantly reduces the total simulation time while preserving computational scalability.
Once all simulations are completed, a reconstruction algorithm is applied to combine the individual 2D results into a unified 3D surface representation. This process preserves the essential geometric and kinematic characteristics of the full 3D model while benefiting from the efficiency of 2D computations.

As a result, the proposed hybrid framework reduces computational time from several days to a few hours, while maintaining a high level of predictive accuracy. This makes it a practical solution for large-scale simulations and detailed parametric analyses.

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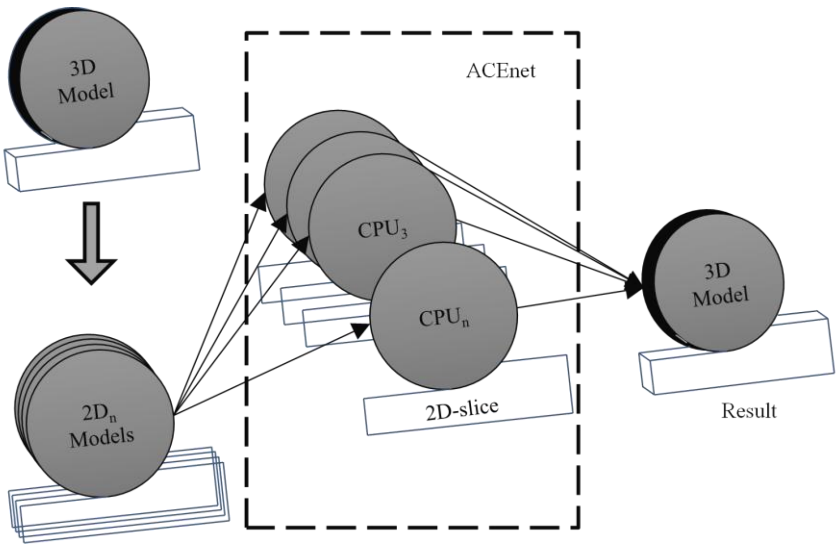

Fig. 2: Schematic representation of the proposed hybrid 2D–3D simulation approach.

The concept of the hybrid framework is illustrated in Figure 2. The original 3D domain is decomposed into multiple 2D slices, each representing a cross-section of the grinding interaction. These slices are simulated independently and subsequently combined to reconstruct the final 3D surface.

4- Results and Discussion

4-1 Comparative Analysis of 2D vs. 3D Results

The numerical results obtained from the simulation frameworks highlight the critical influence of model dimensionality on the prediction of key grinding parameters. To provide a clearer interpretation, the comparison is presented separately for constant and stochastic grinding wheel models.

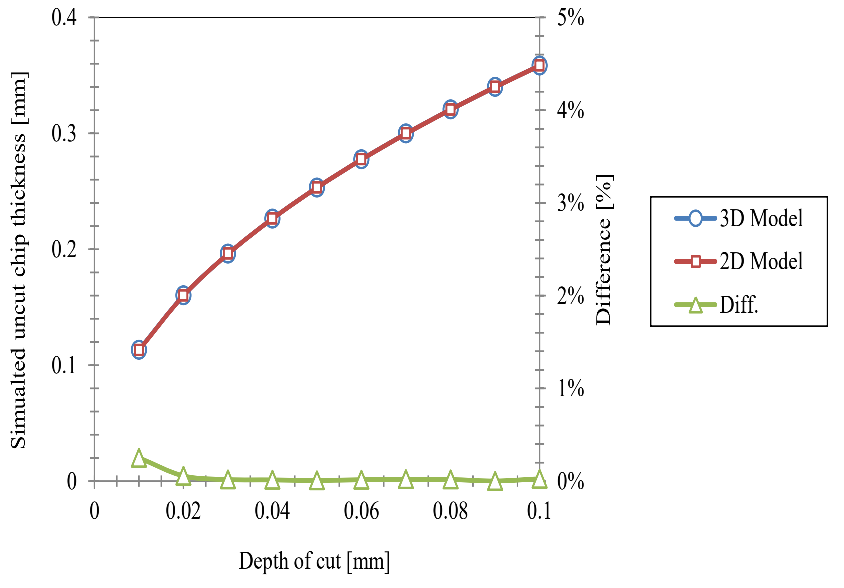

Fig. 3: Comparison of uncut chip thickness versus depth of cut for 2D and 3D models under constant conditions.

As illustrated in Figure 3, both 2D and 3D models exhibit nearly identical trends in uncut chip thickness under constant parameter conditions. This indicates that, for idealized cases, the simplified 2D representation is capable of reproducing the fundamental kinematic behavior of the grinding process.

However, when stochastic variations in grain geometry and distribution are introduced, a clear divergence emerges. The 2D model consistently underestimates the uncut chip thickness, primarily due to its inability to capture off-plane grain interactions. In contrast, the 3D model accounts for the full spatial engagement of grains, leading to more realistic predictions.

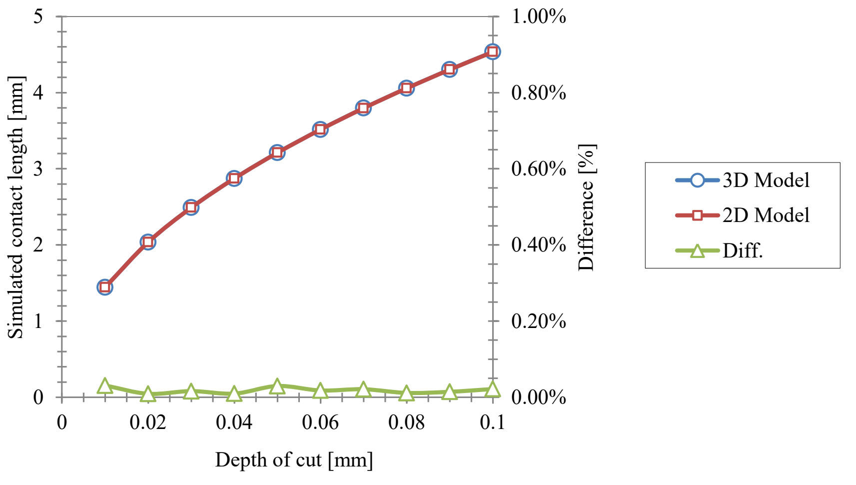

Fig. 4: Comparison of contact length versus depth of cut for 2D and 3D models under constant conditions.

A similar trend is observed for contact length, as shown in Figure 4. While both models remain consistent under simplified conditions, the 3D model predicts higher contact length values in stochastic simulations. This can be attributed to the inclusion of lateral grain distribution, which increases the effective interaction zone between the grinding wheel and the workpiece.

4-1-1 Constant Parameter Models

As shown in Figures 3 and 4, the agreement between the 2D and 3D models is excellent when grain size, spacing, and protrusion height are kept uniform. The deviations are minimal, with differences of approximately 0.25% for uncut chip thickness and 0.03% for contact length [2].

These results suggest that, for idealized grinding conditions, the additional computational cost of 3D modeling may not be justified, and 2D simulations can serve as an efficient and reliable alternative.

4.1.2 Stochastic Parameter Models

As shown in Figures 5 and 6, the limitations of the 2D model become more pronounced when the stochastic nature of the grinding wheel is considered. At a depth of cut of 0.1 mm, significant discrepancies are observed, with differences reaching 60.3% for uncut chip thickness and 19.7% for contact length [2].

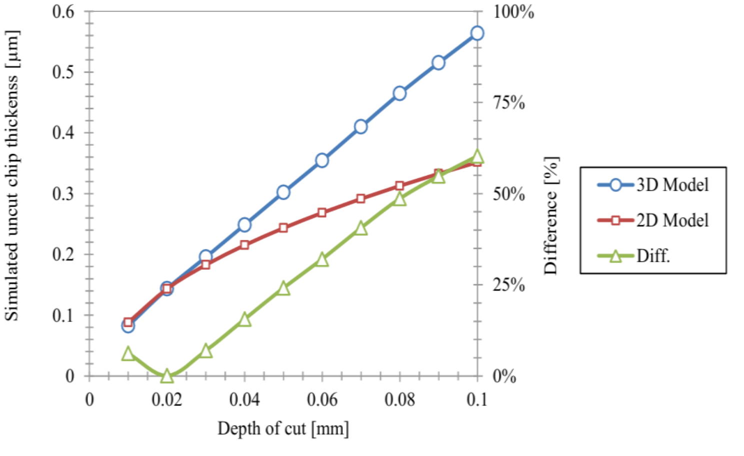

Fig. 5: Comparison of uncut chip thickness versus depth of cut for 2D and 3D models under stochastic conditions.

As shown in Figure 5, the divergence between the 2D and 3D models increases progressively with depth of cut. While both models follow a similar trend, the 2D model consistently underestimates the uncut chip thickness. This deviation becomes more pronounced at higher depths of cut, highlighting the inability of the 2D model to capture off-plane grain interactions.

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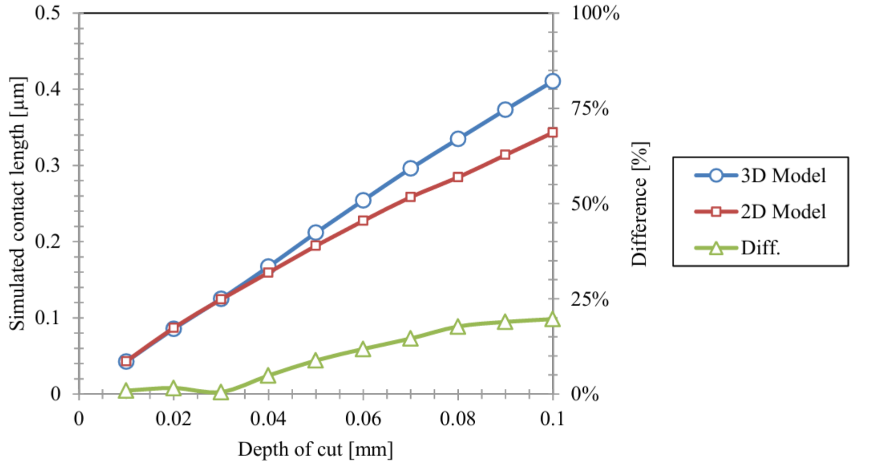

Fig. 6: Comparison of contact length versus depth of cut for 2D and 3D models under stochastic conditions.

A similar behavior is observed for contact length, as illustrated in Figure 6. The 3D model predicts higher contact length values due to the inclusion of lateral grain distribution and multi-directional interactions. In contrast, the 2D model remains limited to a single plane, leading to systematic underestimation. This behavior can be explained by the inherent assumptions of the 2D model. Since the simulation is restricted to a single plane, only grains intersecting that plane are considered active. In reality, however, grains located outside this plane may still contribute to material removal through off-center interactions. These contributions are fully captured in the 3D model but completely neglected in the 2D representation.

4.2 Surface Profile and Roughness Validation

The validity of the 3D stochastic model was assessed through comparison with experimental grinding data. For a depth of cut of 0.09 mm, the simulated surface roughness (Ra = 2.1 µm) shows strong agreement with the experimental value (Ra = 1.9 µm).

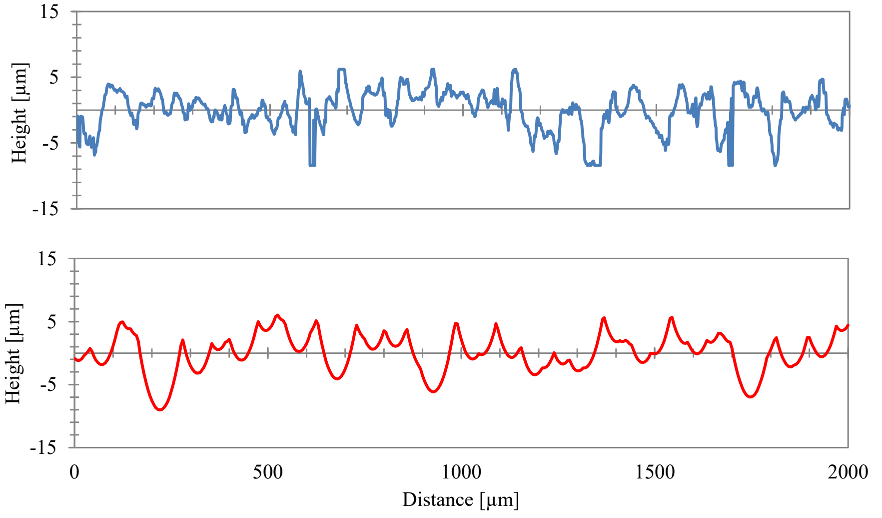

Fig. 7: Experimental (above) and simulated (below) surface profiles showing close agreement.

Figure 7 demonstrates that the 3D simulation is capable of accurately reproducing the surface profile, including both amplitude and frequency characteristics of the surface irregularities. This confirms the ability of the model to capture the essential physical mechanisms governing surface formation.

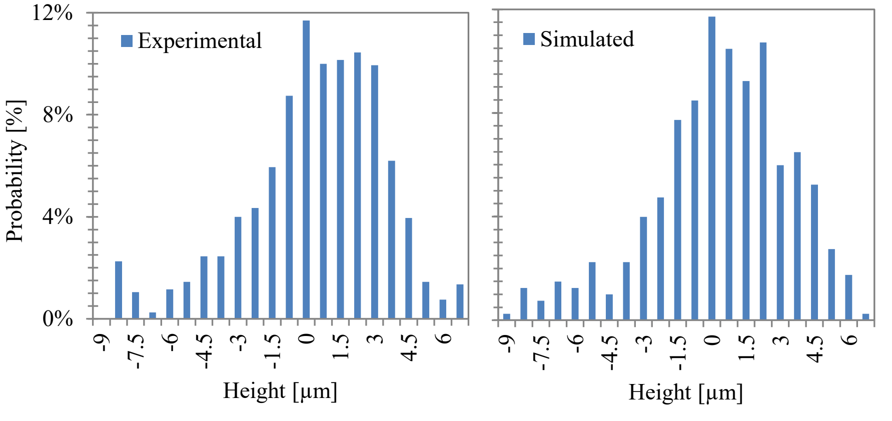

Fig. 8: Height distribution histogram of simulated and experimental surfaces.

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The statistical distribution of surface heights, presented in Figure 8, follows a near-normal distribution within the range of -9 μm to 7 μm. This behavior is consistent with experimental observations and further validates the stochastic representation of grain interactions in the simulation.

4.3 Active Grain Distribution

One of the key findings of the 3D stochastic simulation is the relatively low percentage of active grains. At a depth of cut of 0.1 mm, only 8.5% of the abrasive grains were found to actively participate in material removal [2].

This indicates that a large proportion of grains either lack sufficient protrusion height or are effectively shielded by neighboring grains. This phenomenon highlights the importance of accurately modeling grain interactions in three dimensions, as it has a direct impact on process efficiency and energy consumption.

4-4 Effects of Dressing on Topography

The dressing process was found to have a significant influence on the grinding wheel topography and, consequently, on the grinding performance.

Fine dressing produces a higher density of active cutting edges, as well as larger effective cutting areas, compared to coarse dressing. The influence of dressing extends to a depth of approximately 80 μm below the wheel surface [2].

- Chip Geometry: The dressed wheel model generates thicker and longer chips, whereas the undressed wheel tends to produce wider chips. This difference reflects the changes in grain sharpness and exposure resulting from the dressing process [2].

- Active Cutting Edges: The proportion of active grains increases substantially after dressing. At a depth of cut of 0.1 mm, the percentage rises from 8.5% in the undressed condition to approximately 27% after dressing [2].

These observations further emphasize the necessity of 3D modeling for capturing the true physical effects of wheel preparation, which cannot be adequately represented using simplified 2D approaches.

http://www.doi.org/10.62341/istj-vol39-1-ar23

5- Discussion of Advantages and Limitations

Compared to conventional approaches that rely solely on full 3D simulations, the proposed hybrid framework offers a more scalable and computationally efficient alternative. By exploiting the inherent structure of the grinding process and decomposing it into manageable sub-problems, the hybrid approach enables high-resolution simulations without the prohibitive cost typically associated with full 3D models. This makes it particularly suitable for industrial-scale applications, where computational resources and turnaround time are critical constraints.

5.1 Computational Efficiency

One of the most evident advantages of the 2D simulation framework is its computational efficiency. A typical 2D simulation requires only 2 to 4 hours on a standard desktop system, making it well-suited for rapid analysis and iterative studies. In contrast, full 3D simulations are significantly more demanding, often requiring between 4 and 5 days on the same hardware. This computational burden has historically limited their use in large-scale parametric studies.

However, the adoption of parallel computing techniques has substantially improved the feasibility of 3D simulations. When executed on high-performance computing (HPC) clusters, the simulation time can be reduced to a range between approximately 1 and 2 hours, depending on the available resources [2]. Furthermore, recent developments—particularly active-point selection methods—have demonstrated that 3D kinematic simulations can achieve sub-minute runtimes without compromising accuracy [4].

These advancements indicate a clear trend toward making high-fidelity 3D simulations more accessible for both research and industrial applications.

5-2 Accuracy and Applicability

Despite their efficiency, 2D models exhibit fundamental limitations in representing the stochastic nature of real grinding processes. The observed error—reaching up to 60.3% in uncut chip thickness—highlights the inability of the 2D framework to account for off-plane grain interactions. As a result, 2D simulations are not suitable for applications requiring high predictive accuracy, such as force modeling, energy estimation, or detailed surface characterization.

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Nevertheless, they remain valuable in specific contexts, particularly for:

- Preliminary parameter screening
- Sensitivity analysis
- Understanding fundamental grain–workpiece interaction mechanisms

On the other hand, 3D simulations provide a much more comprehensive representation of the grinding process and are essential for:

- Predicting full surface topography parameters (Sa, Sq, Ra)
- Evaluating the effects of wheel dressing
- Analyzing the spatial distribution of active grains and their influence on wheel wear and process stability.

This distinction clearly positions 2D models as exploratory tools, while 3D models serve as predictive and validation-oriented frameworks.

5-3 Comparison Summary

A summary comparison between the 2D and 3D simulation frameworks is presented in Table 1.

Table 1: Comparison of 2D and 3D Grinding Simulation Frameworks

Feature	2D Simulation	3D Simulation
Computational Time (Desktop)	1-2 hours	4-5 days
Computational Time (Parallel/HPC)	N/A	1 hour – 2 hours
Accuracy (Constant Model)	High (>99.7%)	Reference
Accuracy (Stochastic Model)	Low (up to 60% error)	High (90–98%)
Surface Prediction	Profile only	Full 3D topography
Primary Use Case	Parameter screening	Process validation

6. Conclusion

This study presented a comprehensive evaluation of two-dimensional (2D) and three-dimensional (3D) grinding simulation frameworks based on the modified Z-map technique, with particular emphasis on their accuracy, computational efficiency, and applicability to realistic grinding conditions.

http://www.doi.org/10.62341/istj-vol39-1-ar23

The results demonstrate that 2D simulations provide a highly efficient and sufficiently accurate representation under idealized conditions, where grain geometry and distribution remain uniform. However, their limitations become pronounced when the stochastic nature of real grinding wheels is considered. In such cases, the 2D model significantly underestimates key process parameters, with errors in uncut chip thickness reaching up to 60.3%.

In contrast, 3D simulations offer a much higher level of physical fidelity, accurately capturing complex grain–workpiece interactions. The predicted surface roughness (Ra = 2.1 μm) shows strong agreement with experimental measurements (Ra = 1.9 μm), confirming the reliability of the 3D stochastic approach.

An important finding of this work is that only a limited fraction of abrasive grains, ranging from approximately 8.5% to 27%, actively participate in material removal. This highlights the highly selective and stochastic nature of the grinding process, which can only be properly represented using three-dimensional models.

Although full 3D simulations are traditionally associated with high computational cost, recent advancements in parallel computing and active-point selection techniques have significantly improved their feasibility. These developments indicate a clear shift toward more practical use of high-fidelity simulations in both research and industrial contexts.

To further address the computational challenges, a hybrid 2D–3D simulation framework was proposed and successfully implemented. The results show that this approach can reduce computational time from several days to only a few hours, while preserving a high level of predictive accuracy. This makes the hybrid framework a promising solution for large-scale simulations and parametric studies.

Overall, this work demonstrates that while 2D models remain useful for preliminary analysis, accurate prediction of grinding behavior under realistic conditions requires either full 3D modeling or hybrid approaches that retain essential three-dimensional interactions.

http://www.doi.org/10.62341/istj-vol39-1-ar23

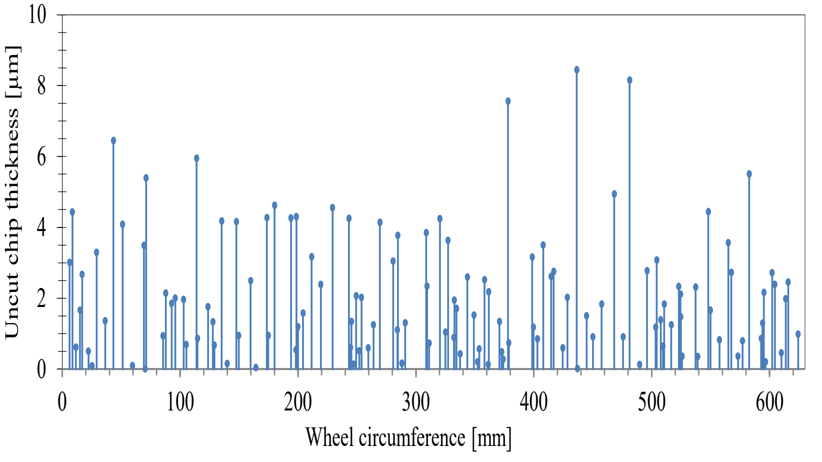

Fig. 9: Distribution of uncut chip thickness for active grains in stochastic model.

Figure 9 illustrates the distribution of uncut chip thickness across active grains. The wide spread of values clearly reflects the stochastic nature of the grinding process, further confirming that simplified 2D representations are insufficient for capturing such variability.

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