Mechanism of Abrasive-Based Finishing Processes

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Various manufacturing industries have been using conventional procedures for finishing the components, such as grinding, honing, lapping, etc., to get the machining components' desired finishing. However, these conventional procedures of finishing are restricted to very few geometries and cannot work on complex and intricate geometries as well as complicated profiles for finishing of high level, which is required while the operation of the component is in process. These limitations and restrictions in the finishing process have led the industries to develop advanced finishing procedures, known as "Abrasive flow machining (AFM)". Advances in technology and refinement of available computational resources paved the way for the extensive use of computers to model and simulate complex real-world problems difficult to solve analytically. The appeal of simulations lies in the ability to predict the significance of a change to the system under study. The simulated results can be of great benefit in predicting various behaviors, such as the wind pattern in a particular region, the ability of a material to withstand a dynamic load, or even the behavior of a workpiece under a particular type of machining.

Keywords: abrasive-based machining processes ; AFM process ; molecular dynamic simulation ; artificial intelligence ; regression analysis

1. Introduction

Metal cutting is considered the most significant procedure where the material removal process is performed by more than one edge to fulfill some of the specific criteria needed to shape the final workpiece in the form of particular geometrical dimensions and surface finish. Even though there has occurred a lot of advancement in the development of machining tools and process controlling and monitoring, there still exists room for improvement in metal cutting processes and procedures for which significant research can be conducted by various metal-forming industries [1]. This may occur due to the optimizing procedures' intricacy, particularly when the materials with higher "mechanical characteristics" are developed and the machinability has not yet been inspected fully [2].

In addition to the material removal and metal cutting process, there is a fine requirement that product surface quality is considerably better since they play a major role in aerospace, automotive, and biomedical industries [3]. Even a small scratch or an uneven burr can cause huge damage to the engine. It may fail the aerospace gadgets or malfunction any of its components, etc. These industries are trying their best to spend a huge amount on the finishing of such components in order to make components that are cutting/burrs marks-free [4]. For the last 40 years, various manufacturing industries have been using conventional procedures for finishing the components, such as grinding, honing, lapping, etc., to get the machining components' desired finishing. However, these conventional procedures of finishing are restricted to very few geometries and cannot work on complex and intricate geometries as well as complicated profiles for finishing of high level, which is required while the operation of the component is in process. These limitations and restrictions in the finishing process have led the industries to develop advanced finishing procedures, known as "Abrasive flow machining (AFM)" [5]. AFM process is used to perform the finishing process of the machining components and its internal features in several engineering materials such as alloys, ceramics, non-ferrous, super-alloys, refractory materials, semiconductors, carbides, quartz, and various other composites, etc., that are considered to be difficult to be done using the traditional processes economically and proficiently [6]. The significance of this AFM process is that it generates the nano-level finishing of the machining components that are essentially desirable at this time. The concept of the AFM finishing procedure was first given by the "Extrude Hone corporation of the USA" in 1960 for the finishing of aerospace components to achieve the desired accuracy. These days, the AFM process is the best technique for finishing intricate geometries, which were never achievable by any traditional finishing tools. Even a lot of study has been conducted by researchers in order to improve the finishing process performed by the AFM [7]. The AFM process efficiently improves the surface finish of the complicated geometry like gears, trim-dies, turbine blades, bio-medical implants, etc. [8][9]. Many researchers have highlighted the potential of the AFM process to finish any complex and freeform surfaces [10][11]. Researchers have also developed a hybrid form of AFM processes, i.e., rotational type abrasive flow machining (R-AFM), to finish the asymmetrical complicated workpiece [12]. Magnetorheological abrasive flow finishing (MRAFF) has also been developed under the umbrella of the hybrid AFM process to finish optical surfaces [13]. Many researchers have employed the AFM and its hybrid variants for surface finishing of metal matrix composite materials, i.e., Al/SiC MMCs [14][15]. Hybrid manufacturing processes, i.e., ultrasonic-assisted machining processes, are also a good solution due to less cutting force required during the machining operation [16]. Ultrasonic-assisted magnetic abrasive finishing (UAMAF) significantly improves the surface roughness as well as the hardness of the workpiece [17][18]. Centrifugal force-assisted abrasive flow machining (CFAFM) is an efficient hybrid machining process to finish cylindrical surfaces with better surface roughness [19].

1.1. An Overview of Abrasive-Based Machining Processes and Their Types

1.1.1. Loose Abrasive-Based Machining Processes

The loose AFM process is considered the most significant approach to finishing the intricate and complex geometries and advanced materials used within industrial practices [20][21]. It is considered to be the recently developed “surface finishing process” that has been used widely in various industrial applications such as defense, aerospace, bio-medical, tool and die, etc. [22]. In loose AFM, no structure exists that connects or links the grains together in the matrix in bonded “abrasive process.” The various standard processes in Loose abrasive processes include AFM, polishing, lapping honing, and abrasive blasting. AFM is also one of the finishing techniques that entail the oil for the particle of abrasive and carrier polymer and assists in eliminating the barriers to acquiring the desired size and shape [14]. Thus, any complicated shape can be easily finished by Abrasive Flow Machining abbreviated AFM. Abrasive flow machining helped researchers to tackle the shortcomings of conventional processes like “grinding,” “lapping,” and “honing” [20]. The problem associated with AFM is its high cost and “low material removal rate MRR,” which makes it laborious and strenuous. AFM processes of finishing techniques have also emerged recently to tackle the challenges and issues such as processes requiring high machining time [23][24][25][26]. **Figure 1** below illustrates the “loose abrasive-based machining” (LAM) process.

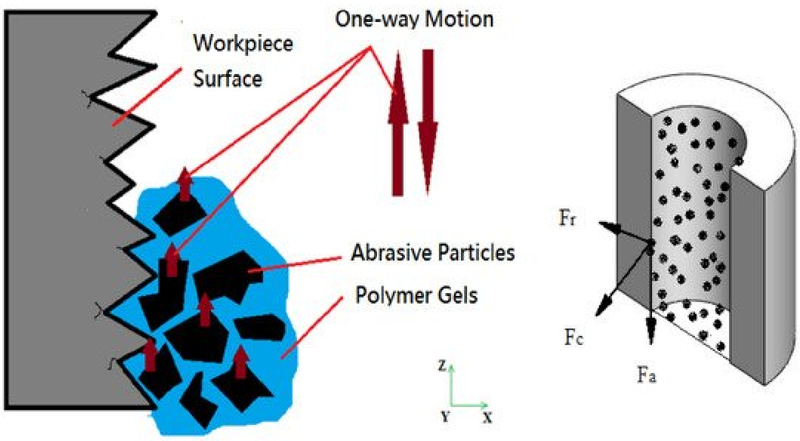


Figure 1. Loose abrasive-based machining process [26].

Figure 2 below signifies the various categories and sub-categories of the loose abrasive-based machining process.

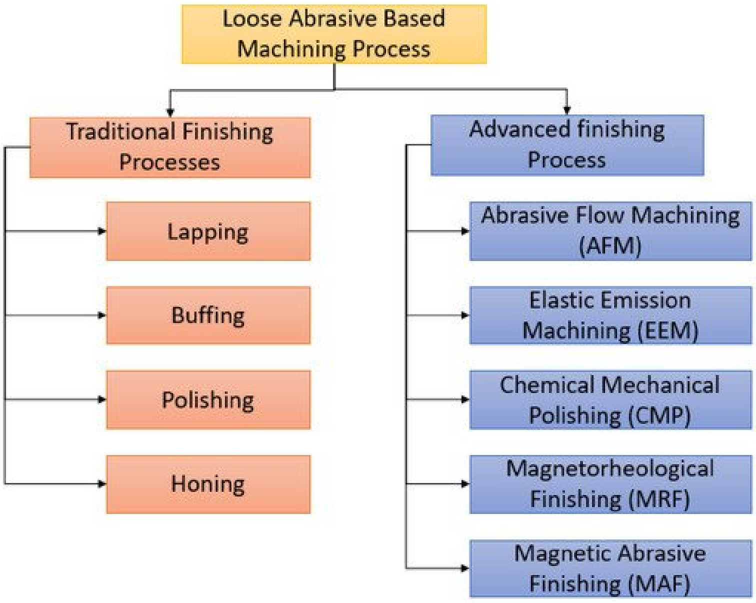


Figure 2. Categories of Loose Abrasive-Based Machining Process.

The machining accuracy of different traditional and advanced machining processes is described in **Figure 3**.

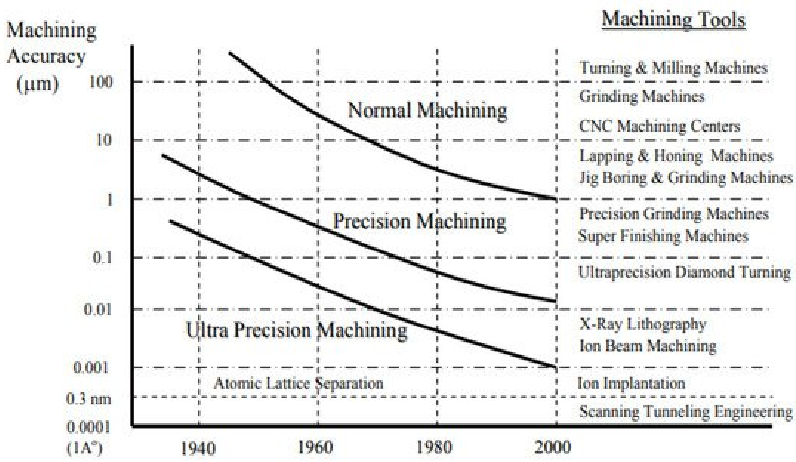


Figure 3. The machining accuracy of different traditional and advanced machining processes [27].

A summary of loose abrasive-based machining processes about their basic principle and process parameters is shown in **Table 1**.

Table 1. Literature summary of loose abrasive-based Machining process with basic principle and process parameters.

S. No.	Loose Abrasive-Based Method		Typical Materials	Principle	Average Surface Roughness (Ra μm)	Application	Ref.
1.	Traditional Finishing Processes	Lapping	Metals	Harden the trapped partials between the surface of the workpiece and a soft counter formal surface	0.05 μm to 2.5 μm	Improving the surface finish in loose abrasive-based machining	[28]
		Buffing and Polishing	Metal and wood	Finishing the surface is performed through a wheel or an abrasive	0.1 μm to 0.41 μm	Smoothing the material	[29]
		Super abrasive machining	Titanium, nickel-based alloys and metal matrix composites, etc.	Finishing of Hard surfaces using polycrystalline diamond (PCD) or polycrystalline cubic boron nitride (PCBN) tools	0.0127 μm–0.203 μm	Hard materials	[28]

S. No.	Loose Abrasive-Based Method		Typical Materials	Principle	Average Surface Roughness (Ra μm)	Application	Ref.
2	Advanced finishing Process	Abrasive Flow Machining (AFM)	Hardened steel	Removing material from the surface of the material using sliding of abrasive particles of another material	0.184 μm	Can deal with complex components	[26] [28] [30]
		Elastic Emission Machining (EEM)	silicon	removing the material atom by atom with no cracks, deformation, or deep indentations	Less than 0.0005 μm	Removing material in loose abrasive-based machining	[28] [30] [31]
		Chemical Mechanical Polishing (CMP)	silicon	A layer is formed between the workpiece and the slurry by chemical reaction. This layer is softer than the material of the original workpiece, which can be easily removed.	0.005 μm to 0.01 μm	used in the finishing of the wafers made from silicon	[28] [30] [32]
		Magnetic Abrasive Finishing (MAF)	silicon nitride	In this process, ferromagnetic particles are mixed with the particles of the workpiece. This mixture is brought close to the surface of the workpiece to be finished.	Less than 0.01 μm	Finishing the surface of nano-chips	[28] [30]
		Magnetorheological Finishing (MRF)	Flat BG7 glass	To finish the surface in this process, magnetorheological fluid (MR fluid) is used. This fluid consists of iron particles, carbonyl iron particles (CIPs), carrier fluid, and abrasive particles. The viscosity of this fluid is increased when it comes under the effect of the magnetic field. The CIPS arrange along the magnetic force line, and then the abrasive particles are entangled within the chains, and their motion causes the material removal	Less than 0.001 μm	Finishing micro/Nano-chips	[28] [30]
		Magnetorheological Abrasive Flow Finishing (MRAFF)		This method is an extended version of MRF. the extrusion of the medium of the magnetorheological polishing is performed through the surface of the workpiece	Less than 0.001 μm	Finishing softer material than MRF	[30] [33] [34]
		Ball end Magnetorheological Finishing (BEMRF)	Metal mirror and glass	for the finishing, this process uses the rotating spot of the stiffened MR fluid	Less than 0.001 μm	Used in the finishing of the complex 3d geometry	[35]

The comparison of surface roughness of traditional finishing techniques s shown in **Figure 4** below.

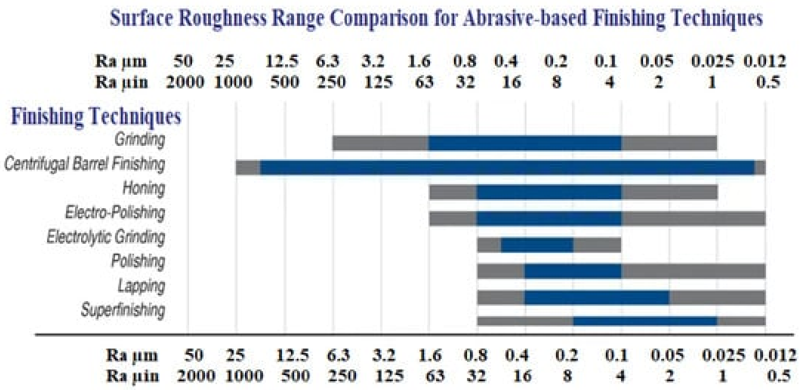


Figure 4. Surface roughness range comparison for traditional finishing processes.

The comparison of surface roughness of advanced finishing techniques, i.e., nano finishing techniques, is shown in **Figure 5** below.

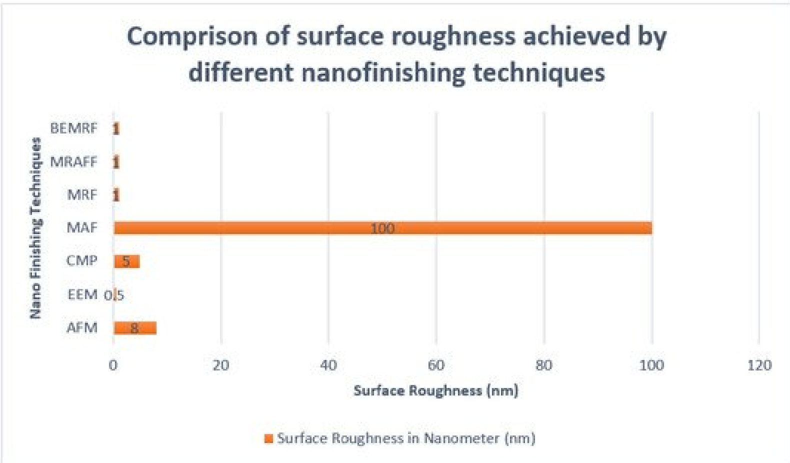


Figure 5. Surface roughness range comparison for nano finishing processes.

1.1.2. Abrasive Flow Machining (AFM)

AFM is considered to be the non-conventional process of finishing that deburrs, polishes, alleviates the recast layers, and has the potential to generate the “compressive residual stresses” at the part where it is difficult to reach with the conventional finishing process. Few of the major applications of AFM include the finishing of various aerospace and medical components, automotive parts, and high-volume generation of electronic parts. Several materials such as soft aluminum, ceramics, tough nickel, and carbides have been micro-machined successfully through this process [36]. The process of AFM gives the high-level surface finish as well as close geometric tolerance at reasonable and economical rates for a significant range of industrial parts and components [37]. One of the basic reasons behind implementing the AFM process is the ability of its media to finish the intricate points in the components where it is difficult to reach using conventional methods. Also, it can follow the “complex contours” and work simultaneously on several edges and surfaces, thus making it more desirable in comparison to the other finishing processes [38]. In the manufacturing process, several mechanical parts undergo one machining operation at least once in order to fulfill a certain function within the environment [39]. Some criteria for the quality of such pieces are desired, such as dimensional, roughness, as well as geometric specifications, etc.

AFM alleviates small quantities of the material through “semi-solid abrasive laden media” across the workpiece. In this process, two vertical cylinders opposing each other extrude the media in both directions (back and forth) across the passage in the workpiece as well as tooling, as shown in **Figure 6**. Here, the media comprises the abrasive grains and that of the semi-solid carrier, where the media acts as a “self-deformable stone” possessing protruding abrasive particles that act as the cutting tools.

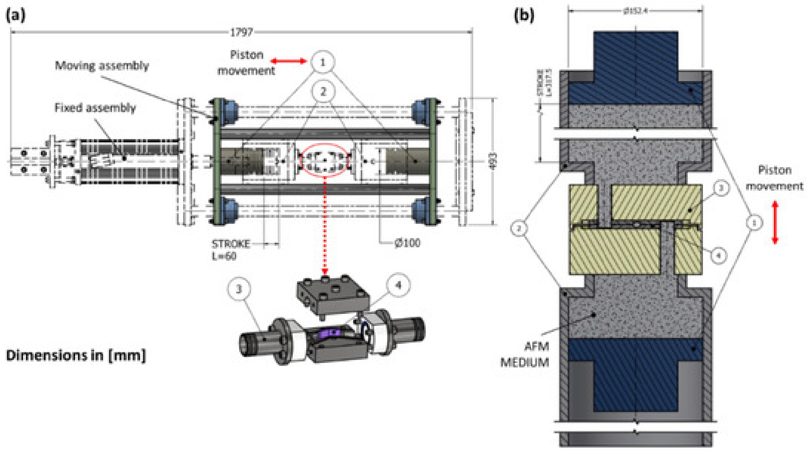


Figure 6. AFM setups: (**a**) V-shape laboratory setup; (**b**) S-shape industrial setup [40].

1.1.3. Developments in AFM Process

The abrasive flow machining process can provide good results for the machining components that need the removal of the defects created by the mechanical or manufacturing processes. The AFM process makes ideal for relief of surface stress, radiusing, polishing, deburring and geometric optimization [41]. Being an essential requirement of industry these days, a large amount of research work has been reported in this domain in literature.

AFM is considered to generate the “self-deforming tool” that accurately removes the extra workpiece material and then finishes the surface from the areas where it is difficult to do so with the conventional machining process [42].

The material removal process comprises three modes of deformation, which are as follows:

- “Elastic deformation”: it correlates with rubbing
- “Plastic deformation (ploughing)”: it correlates with the material being displaced without being alleviated.
- “Micro-cutting” [43][44][45]

Initially, in [46], the authors developed the one-way process of AFM where the medium traveled in a single direction and termed it to be the simplest type of AFM that consumes the least time during the finishing process [47][48][49][50]. It was observed that surface roughness could be minimized to 90% on the machined, cast, or EDM surface having the “dimensional tolerance” up to or ±0.005 mm [51][52].

In order to get a better radiusing and finishing action not only in the inner but outer surface as well as the components, two way AFM process of finishing was developed [53][54]. Its basic operation involves two horizontal or vertical hydraulic cylinders that lie opposite each other and are placed in between the work piece with the help of suitable fixtures, as illustrated in **Figure 7**. The pistons in the cylinders are used to make the “abrasive laden medium” move back and forth on the surface that needs to be finished. In this way, the finishing process is carried out in a two-way AFM operation.

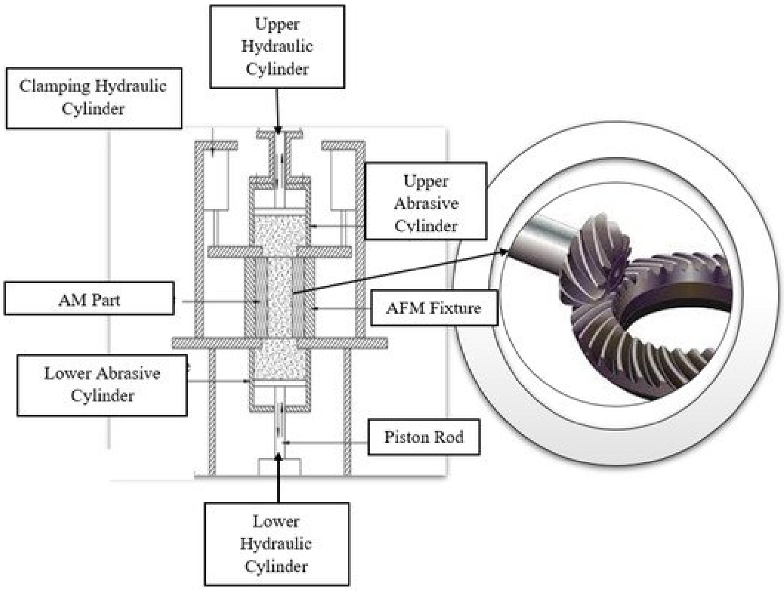


Figure 7. Schematic of two-way AFM process.

In [55], another development was made regarding the oscillatory motion of the workpiece. With oscillations to keep going, the work piece hits the "abrasive medium" with the "eccentric path" that causes the intricate and complex structure to make an interaction fully and completely with that of the abrasive medium, which results in the same (equal) abrasion on each side of the components. In [56], an AFM setup has been developed on the lathe to carry the experiment on brass as well as aluminum. It was observed that the dominant factors are the "abrasive concentration" in the medium, followed by the mesh size, speed of the medium flow, and the number of cycles. A lot of improvement could be seen in the case of materials that were soft, considering the surface roughness enhancement. In [57], the temperature has been considered to be the most influential parameter in the AFM process regarding work efficiency; with the escalation in no. of cycles, the medium temperature increases, which means the decrease in the medium viscosity occurs with the increase in no. of cycles. In work, it has been presented that in AFM testing, an increase in no. of cycles significantly decreases the material removal rate (MRR) as well as surface roughness, thus reducing the efficiency [58].

In order to enhance the process performance and control the rheological properties, scientists and researchers have designed and developed several AFM process variants [59][60] by combining and incorporating the basic AFM operation with that of the traditional/non-traditional flow machining operation. The process of AFM has been classified as per the energy and forces used within the process [61].

Other than the above-mentioned four types of AFM process, there have also been developed some other AFM variants in order to compensate for the MRR and also for a longer finishing time. The variants of the AFM process have few external assistants, such as ultrasonic vibrations [62][63][64], the rotational effect [65][66][67], magnetic field assistance [39][68][69], and also the hybrid variant of the AFM process [54][70][71][72]. The external assistance is found to show the increase in the finishing force [73][74][75], abrasive velocity, enhancement in the contact length among the work surface as well as abrasive, active density of abrasive, or utilization of the synergic effect of two processes in order to eradicate the material [76]. These effects result in enhancing the finishing time, MRR [62][63], and surface roughness. The further classification of the developed AFM variants has been shown in **Figure 8** below.

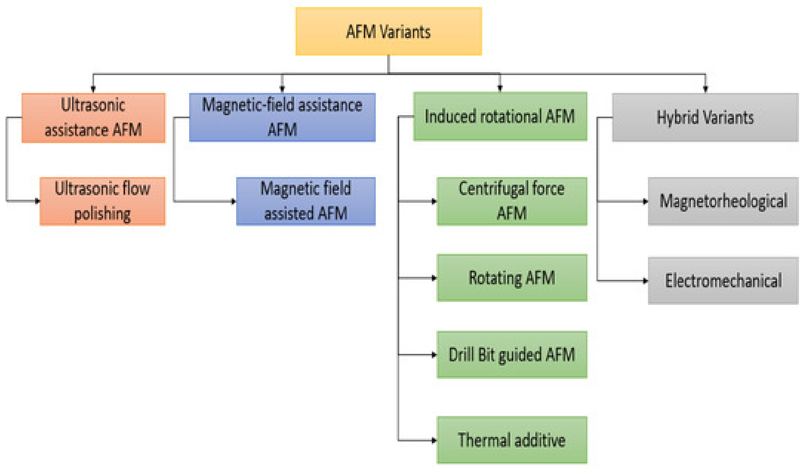


Figure 8. Classification of AFM variants.

A summary of the differences and similarities of the different AFM process variants is shown in **Table 2**.

Table 2. A summary of the differences and similarities of the different AFM process variants.

S. No.	AFM Variants	Working Principles	Working Polishing Fluid (Media)	Commercial Process Names
1.	Ultrasonic-assistance	Use of ultrasonic vibration along the AFM fixture	Viscoelastic polymer-based media	Ultrasonic float polishing (UFP) Ultrasonic-assisted AFM (UAAFM)
2.	Rotational-assistance	Rotating the AFM fixture	Viscoelastic polymer-based media	Rotational AFF (R-AFF) Drill bit guided AFM (DBG-AFM) Helical AFM (HLX-AFM)
3.	Magnetic-assistance	Use of permanent magnet	Magnetic abrasive-based media	Magnetic AFM (MAFM)
4.	Magnetorheological assistance	Use of Electro-magnet and magnetorheological (MR) fluid	MR fluid-based media	Magnetorheological AFF AFF (MRAFF) Rotational-MRAFF (R-MRAFF)
4.	Electro-chemical assistance	Use of Electrochemical machining process along with AFM process	Electrolytes and Viscoelastic polymer-based media	Electro-chemical assisted AFM(ECAFM) Electro-chemical and Centrifugal force-assisted AFM (EC^2A^2FM)
5	Centrifugal force assistance	Use of Centrifugal forces	Viscoelastic polymer-based media	Centrifugal force-assisted AFM (CFAAFM) Thermal Additive centrifugal AFM (TACAFM)

In order to give the best control on the AFM processes, the selection of the parameters of the process is necessarily required. This entry has segmented the AFM process parameters into three main categories. The classification of these three main AFM parameters, including machine, medium, and workpiece [77][78][79]. Here, the machine decides the level to which the abrasion can be processed through “viable extrusion pressure,” flow rate, flow volume, and also the number of cycles [80][81]. “Rheological properties” of “abrasive laden medium” are the ones that signify the amount of abrasion. The grit size, viscosity, temperature, and polymer to dilute are considered to be the parameters for comprehending the rheological properties of the MR fluid. Next comes the workpiece that is finished by the AFM process. The properties of the workpiece, such as material type, roughness value, and also geometry, tell the machining time and abrasive type to be used [82].

Summary of the performance analysis of the AFM process regarding their process parameters is shown in **Table 3**.

Table 3. Literature summary of performance analysis of the AFM process regarding their process parameters.

S. No.	Ref.	Typical Materials	Application	Surface Roughness (μm)
1.	Guo et al., 2020 [83]	Inconel 718	AM parts	Ra 0.1 μm was the final surface roughness value.
2.	Mali et al., 2018 [84]	ABS	FDM printed parts	Change in Ra 21.37 μm for the external surface and 6.27 μm for the internal surface was found.
3.	Subramanian et al., 2016 [85]	Co-Cr alloy	Bio-implant, i.e., Hip Joint	It was found that the surface roughness decreased from beginning R, value 502 nm to final R, value 39 nm.
4.	Kumar et al., 2015 [86]	Ti-6Al-4V	Bio-implant, i.e., Knee Joint	The final surface roughness was measured to be 35–78 nm.

The typical defects during different manufacturing processes for electronic components, pipes, welding parts, and textile materials can be improved using the abrasive-based machining process, i.e., the AFM process and its variant processes, as shown in **Figure 9**.

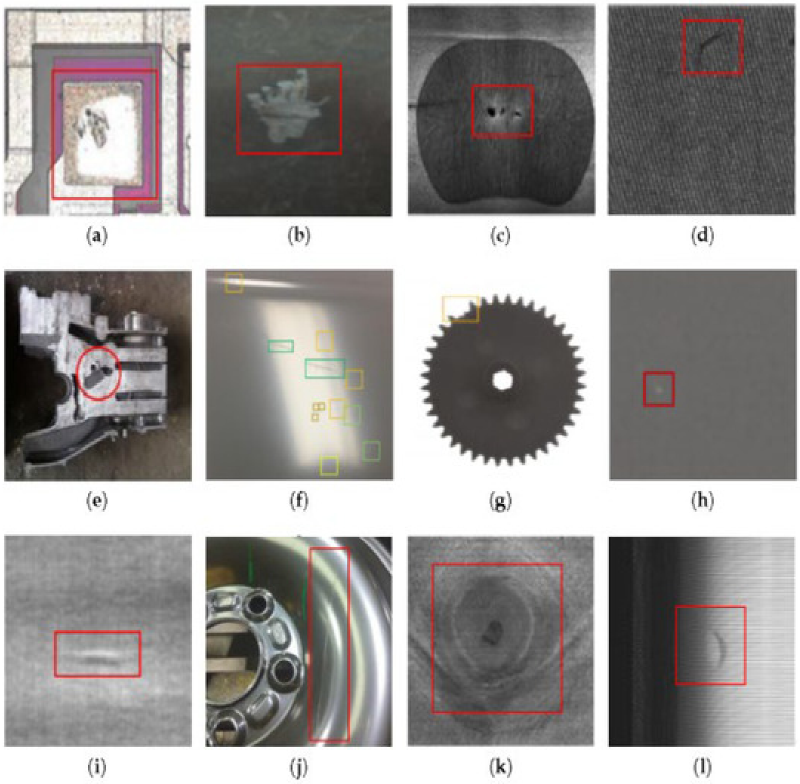


Figure 9. Defects in different areas: (**a**) metallization peels off of electronic components. (**b**) pipeline corrosion. (**c**) defective with gas pore. (**d**) defect big knot of textile materials. (**e**) shrinkage and porosity defect of Casting. (**f**) In the car body, defects in green, yellow, and orange bounding boxes are scratch, cratering, and hump. (**g**) Lack of defect of gear. (**h**) light leakage defect on mobile screen [25]. (**i**) Convexity defect in aluminum foil. (**j**) Scratch defect of the wheel hub. (**k**) Branch defect of wood veneer. (**l**) Bubble defect of the tire sidewall [87].

2. Mathematical Modeling and Simulation Approaches for Abrasive Machining Processes

Recently, computer simulation applications have proved their efficiency in solving complex problems in Engineering. Different techniques of modeling and simulations are considered widely in the Industries, such as “computational fluid dynamics (CFD)” [83][88], “discrete element method (DEM),” “finite element method (FEM),” “artificial neural network (ANN)” [14], “multi-variable regression analysis (MVRA)”, “response surface analysis (RSA)” and “Stochastic modeling (SM)” [89]. These techniques have several applications in the industrial process, such as predicting the behavior of the material removal in loose abrasive-based machining [90]. The results obtained from the modeling and simulations pave how to optimize the process parameters that affect the finish of the workpiece. Several researchers have prominently worked on the “mathematical modeling and simulation” of “loose abrasive-based finishing processes.” Several experimental as well as computational techniques and approaches have been performed to analyze the ideal and optimal procedural parameters [91][92][93][94].

Classification of Modeling and Simulation Techniques for Abrasive-Based Machining Processes

The modeling and simulation-based techniques for LAM may be classified based on the used techniques, i.e., “computational techniques and statistical techniques Petare et al. have also classified several simulation techniques [95], which are shown in **Figure 10**.

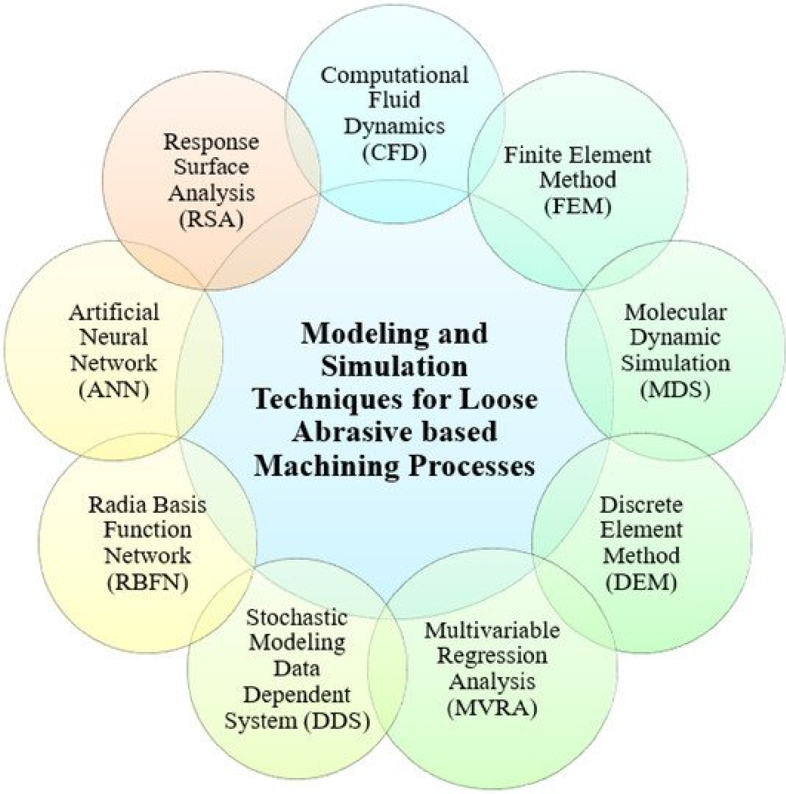


Figure 10. Modeling and simulation tools and techniques for “loose abrasive-based machining”.

3. Review of Simulation Techniques for Abrasive-Based Machining Processes

3.1. Computational Fluid Dynamics (CFD)

This approach is applied to simulate the fluid flow problems in any system aided by numerical methods by integrating the problem’s equations. The characteristics of shear-thinning, Newtonian, non-Newtonian, or the Maxwell fluid are considered while choosing the equations of Navier-stokes to model the flow problem. This method is also applied to take various flow channel geometry into account, locate the optimum parameters for the process, and reduce cost. The simulation performed by Computational fluid dynamics is performed using the available commercial software such as ANSYS ACE, ANSYS CFX, and ANSYS FLUENT using Ansys 2021 R1 software version developed by “Ansys”, was founded in 1970 in western Pennsylvania, United States of America. The general working steps that happen inside the software to apply the CFD approach are shown in **Figure 11** below.

Figure 11. Steps for applying the CFD in software.

3.1.1. Pre-Processing

In this step, the model of CAD that defines the fluid domain in researchers' problem, including any solid boundaries, is prepared first. This step is followed by giving the CFD solver’s required initial and boundary conditions to run the simulation. The other conditions, including the physics needed for the problem along with the meshing conditions, are also fed to the commercial code used for the CFD simulation of the problem. This initial step of creating the CAD model can be performed under the same roof within the software used for the flow simulation itself [96].

3.1.2. Meshing

Meshing is a process of discretization where the fluid volume is converted into many more minor elements or volumes. However, many discretization methods are available, and most CFD software uses the Finite Volume Method (FVM), while some exceptional CFD tool uses the Finite Element Method (FEM). The Meshing mechanism involves sub-dividing the extensive computational domain into many discrete cells called finite volumes (or finite elements if FEM occurs) depending on the CFD toolbox used. The mesh can range from structured or unstructured, uniform or non-uniform, and even with multiple elements like hexahedral or polyhedral in the mesh domain. Meshing remains the main paramount parameter for a CFD simulation to work as desired. Any irregularity in the mesh will crash the simulation when run by the solver [96].

Due to the complexity of Partial differential equations, it is difficult for them to be solved using the computer; therefore, they are converted to another form to be solved in the computer. This process is called discretization, which provides getting continuous equations. By solving a matrix, the algebraic equations can be obtained from the Partial differential equations, and to do that, it is required to identify points. The discretization method is also known to be the “Finite volume method.”

3.1.3. Solving

This step is where the actual application of the CFD technique happens. During this step, the CFD software solves the unknowns present in the Navier Stokes equations. The linear system of equations is solved iteratively, coming up with a better value after each iteration. When explicating the integration scheme, the uncoupled equations can result from the linear system, whereas the coupled equations can result from the implicit equation. With turbulent flow problems, k-epsilon and k-w equations are solved used, and with a laminar flow, the normal Navier-stokes equation is solved.

3.1.4. Post-Processing

The results are obtained in this final step, where the pictorial depiction of the flow parameters is exported and used to study the problem further. Many plots from various sections depicting the distribution or the flow parameters are conducted in post-processing using inbuilt tools or open-source tools like ParaView.

With the advancements coming up in the industrial process, there is an essential role for the process safety in operation and the design of the process facilities. A significant effort was paid to ensuring that “chemical process industries” are at the safest and most secure workplaces among several other industries. However, there is a requirement to analyze the safety of the process mechanism to predict the scenarios. Using experiments to quantify the process safety mechanism is considered to be insufficient as it is highly “resource-intensive.” Fortunately, with the increase in the capabilities of the computation and the enhancement in the “Computational Fluid Dynamics (CFD)” tools, the study of hazardous scenarios and the fundamental mechanics have been improved [97] and has become sophisticated [98]. This approach can model the fluid by solving numerical equations besides capturing the effect of viscosity. CFD can also predict chemical reactions, mass and heat transfer, and fluid flow [99][100]. CFD also has several applications in modeling and simulation in the engineering field [101].

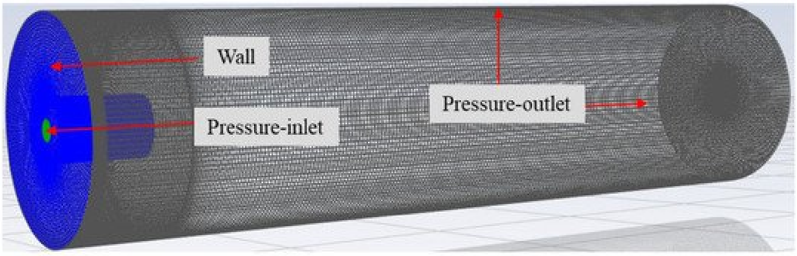
3.1.5. Applications

The thermodynamic and hydrodynamic performance of crude oil before heating in refineries is impaired by fouling. There are inappreciable fouling levels at the early stage of fouling which cannot be determined due to the lack of data from the experiments. Therefore, computational fluid dynamics (CFD) is applied for a better understanding. The CFD technology can account for the chemical reaction, the turbulent flow, and the aging in the tubes present in the heat exchanger. The study [102] simulated three-dimensional CFD under different operating conditions to predict the deposition rates and determine the importance of the fouling mechanism. The interaction between the processes of precipitation fouling and the chemical processes can be characterized by the “interference factor” used to evaluate the suppression extent of the chemical mechanism [102].

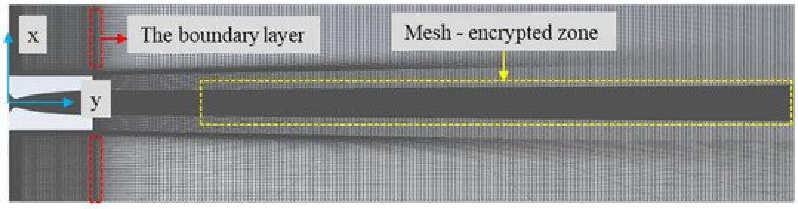
The firing range depends critically on the ventilation systems for exposure to ammunition refuse personnel. CFD is used to simulate the ventilation system and predict airflow patterns. The purpose of this model is to identify back circulation, which emits fire. The validation of the solution of the model and the input parameters of the model are the values measured at several locations. It has been evaluated using the analysis of the massless particles fired at various heights corresponding to kneeling, standing, and prone firing positions. Using the recommended technical guidance for the ventilation of the firing ranges of the small arms compared to the dynamic flow of the system, different predictions are finished. The results showed that the particles return behind the shooter [103]. The air velocities of lower supply correspond to the particle’s successful movement and the uniform flow under investigation in a small firing range. It has been demonstrated that the models of CFD are advantageous as it provides optimization in the air velocity of the supply and enhances the design standards [104]. CFD is also used to model the 3D Concrete Printing to predict the shape of cross-sectional 3D printed segments, which can be achieved through the simulations of “virtual printing.” It has been found that the numerical results of CFD are appropriate to the results of the performed experiments [105].

CFD has the edge over the other modeling methods because of the sophistication available at its disposal. The angle of the impact made by the abrasive particles upon hitting the target surface in Ultrasonic Assisted Abrasive Flow Machining

(UAAFM) could be visualized from the simulation results, and its outcome is therefore evaluated. With the results obtained from the CFD model of the UAAFM, the effect of the temperature rise on the media stability can be predicted, and major decisions could be undertaken [106]. The abrasive wear on a turbine blade's surface can also be evaluated, helped by CFD simulation. The study helps to identify the effects of the size and shapes of the quartz particles on the abrasive and corrosive attrition of the blade [107]. Kim et al. have investigated the deburring of AL6061 material using the AFM process. The authors have conducted the experimental study and three-dimensional CFD simulation of the deburring process and compared both experimental as well as numerical results [108]. Fu et al. have also investigated the rheological and finishing behavior of AFM media using the experimental study as well as CFD simulation study [109]. Pradhan has compared the experimental and CFD simulation results to predict erosion behavior during hot abrasive jet machining (HAJMing) [110]. Similarly, authors have modeled the HAJMing process using CFD analysis [111]. Amar et al. developed the analytical and numerical models for abrasive water slurry jet machining (AWSJM) to fabricate the micro-channel using experimental study and CFD simulation, respectively [112]. Zou et al. simulated the precision machining of straight internal gear using the large eddy simulation method on the CFD platform [113]. Chen et al. [114] have characterized the motion of abrasive particles using CFD-DEM modeling for the abrasive air jet machining process. The authors have analyzed the effect of nozzle pressure ratio (NPR) on the flow field of abrasive particles and stress distribution on the workpiece for the optimum parameters of abrasive air jet machining. The mesh model of the physical model used for CFD-DEM modeling and a few important simulation study results are shown in **Figure 12**, **Figure 13** and **Figure 14**.



(a)



(b)

Figure 12. Structural meshes: (**a**) Three-dimensional view of the computational domain and (**b**) axial profiles [114].

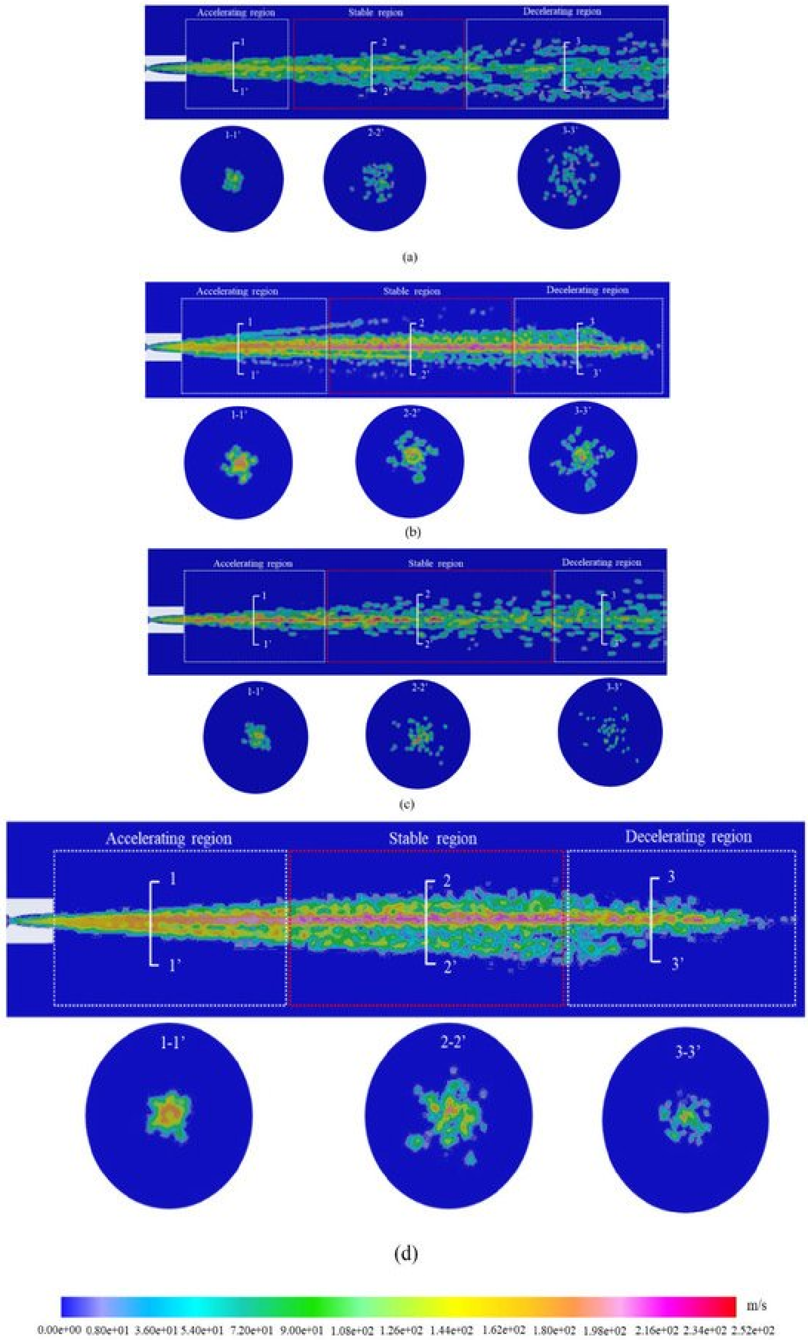


Figure 13. Abrasive particle velocity contour map: (**a**) NPR = 0.6, (**b**) NPR = 1, (**c**) NPR = 1.12 and (**d**) NPR = 2 [114].

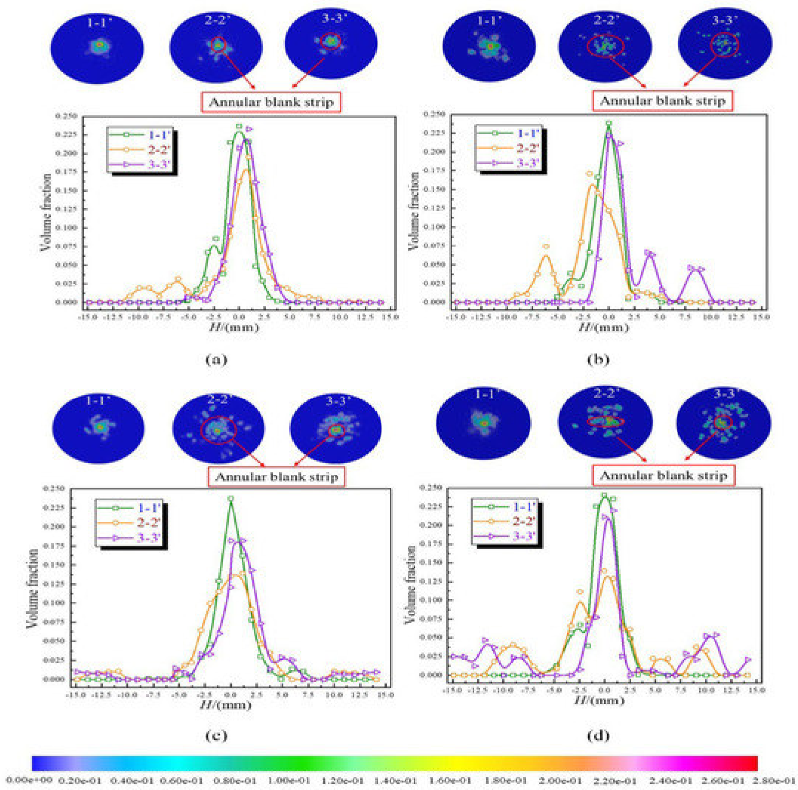


Figure 14. Volume fractions of abrasive particles: (**a**) NPR = 0.6, (**b**) NPR = 1, (**c**) NPR = 1.12 and (**d**) NPR = 2 [114].

Zhang et al. have simulated the behavior of visco-elastic AFM media on micro-slit structures using the CFD simulation technique. The authors have concluded that the flow time (21 s), which was calculated at a velocity of 1.2 mm/s, further demonstrated the polymer chains' remaining stretched state [115]. Similarly, the authors have also simulated the flow of abrasive media using the CFD simulation technique by adopting the carreau-yasuda and wall slipping models. The rheological behavior of AFM media is affected using a material removal mechanism [116]. The mesh model and a few results of these CFD simulations are shown in **Figure 15** and **Figure 16** below.

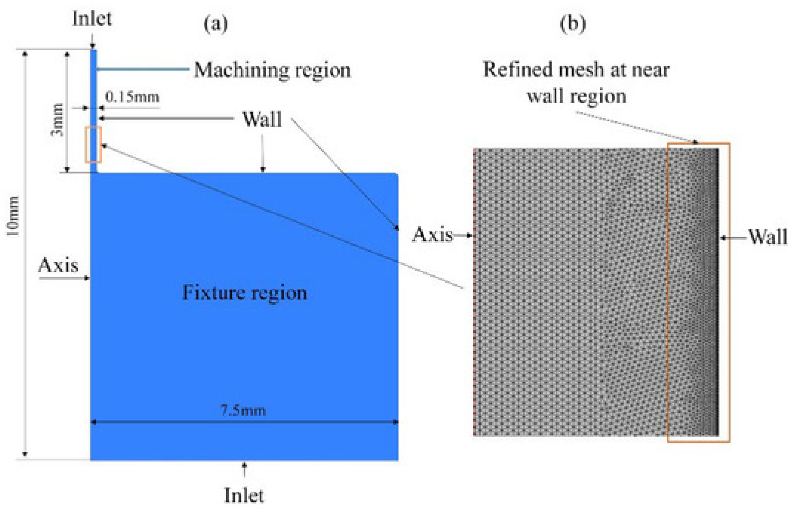


Figure 15. (**a**) The 2D axisymmetric geometry model of a micro hole and (**b**) the mesh distribution [116].

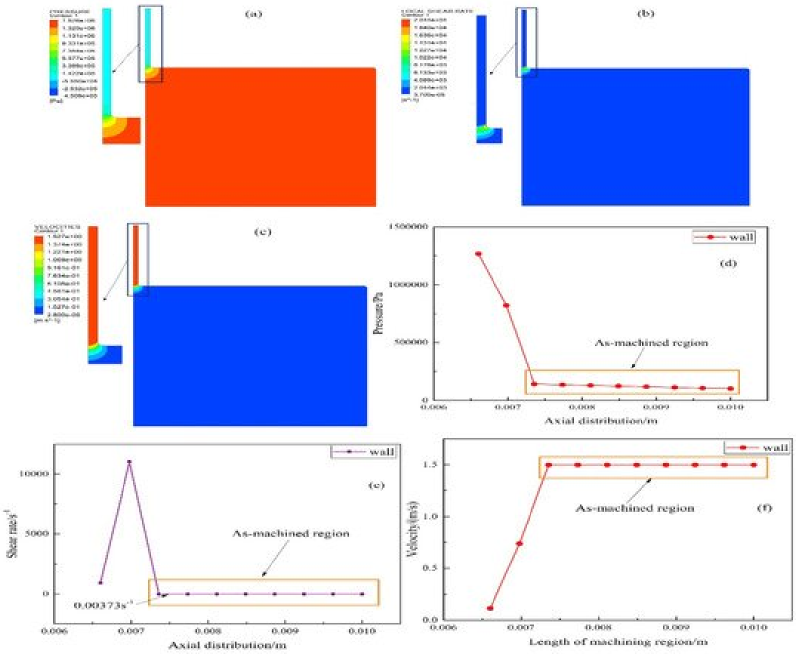


Figure 16. Results of the flow simulation (**a**) pressure distribution, (**b**) shear rate distribution, (**c**) velocity distribution at the fixture region and as-machined region, as well as the (**d**) pressure curve, (**e**) shear rate curve, and (**f**) velocity curve at the wall of the as-machined region [116].

Zhang et al. [117] numerical investigated the machining (AFM) of micro-porous structures using the CFD simulation technique by Brid-Carreau model coupled with mixture and discrete phase models. The authors have demonstrated the simulation results and surface morphology for the finishing of the micro-hole, as shown in **Figure 17**, **Figure 18** and **Figure 19**.

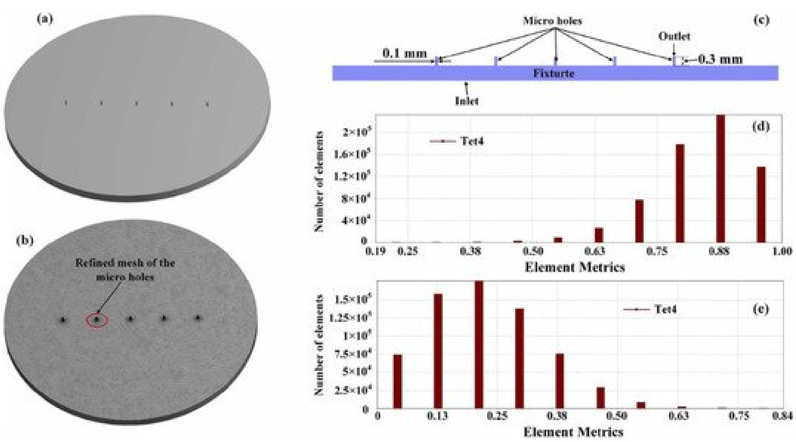


Figure 17. (**a**) The three-dimensional view of the media's flow channels; (**b**) the mesh distribution, and (**c**) the 2D cross-section of micro porous structures, as well as the mesh metrics of (**d**) element quality and (**e**) skewness [117].

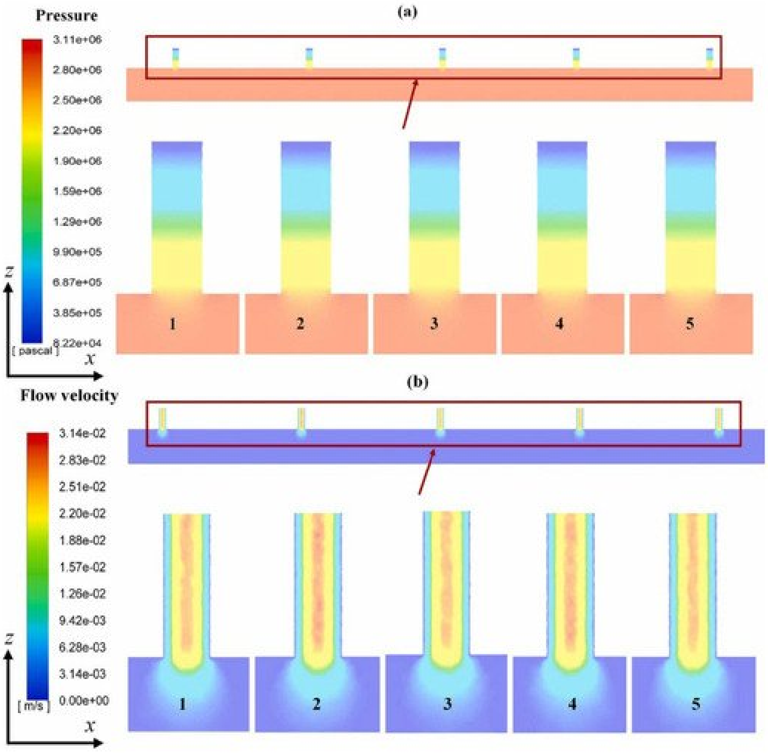


Figure 18. CFD simulation results of (**a**) pressure and (**b**) flow velocity in micro-porous holes [117].

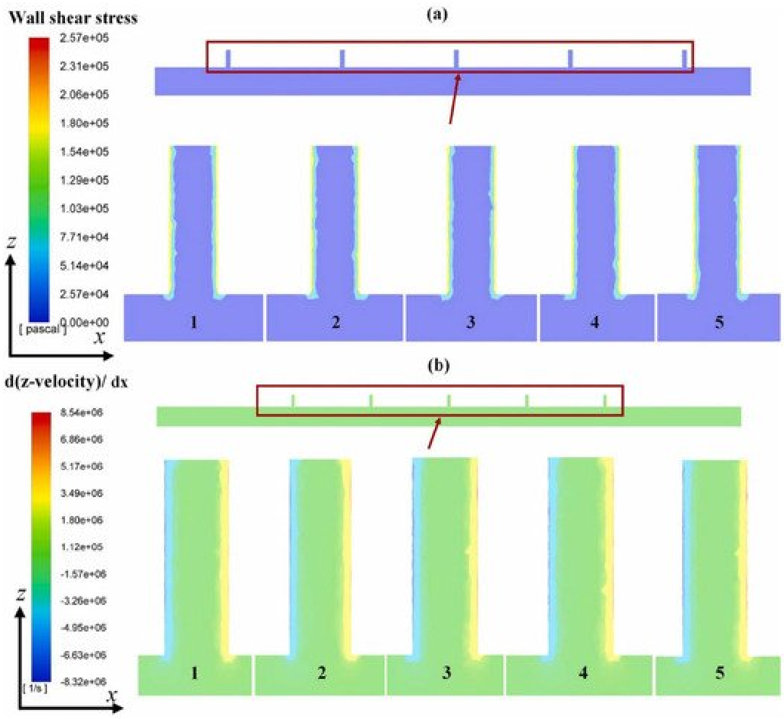


Figure 19. CFD simulation results of (**a**) wall shear stress and (**b**) change rate of the flow velocity along z direction (axial direction) relative to x direction (radial direction) [117].

Zhu et al. [118]. used the double cosine kernel function (SCKF) to develop semi-resolved CFD-DEM for investigating abrasive air jet (AAJ) and studied the particle-scale distribution information in the nozzle of the AAJ machine. Some important results of this simulation study are shown in **Figure 20** and **Figure 21** below.

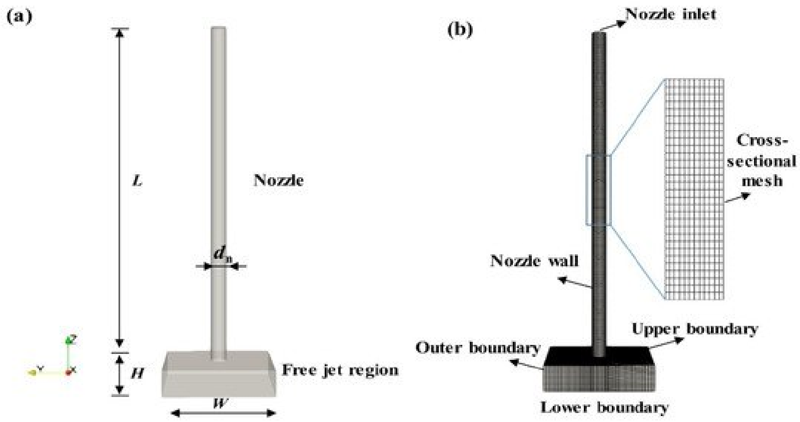


Figure 20. The geometry and boundaries of the computational domain and the numerical meshes: (**a**) Schematic diagram of the computational domain, (**b**) the mesh distribution and boundary settings for the AAJ simulation [118].

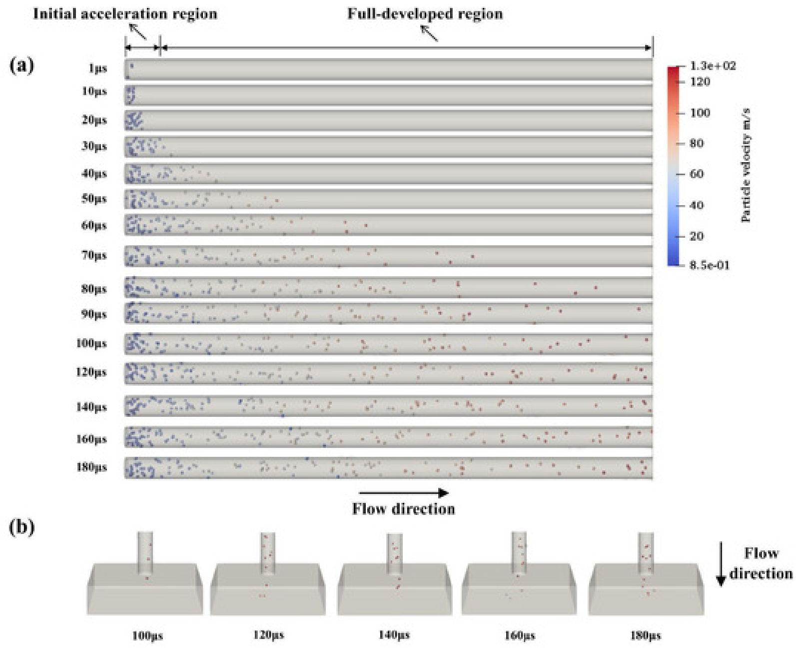


Figure 21. Evolution of particle jet flow along the jet flow direction in the AAJ micromachining. (**a**) The flow pattern inside the AAJ nozzle and (**b**) the particle distribution after the particles leave the nozzle exit [118].

The summary of CFD-based modeling and simulation of the loose abrasive-based method is shown in **Table 4**.

Table 4. Summary table of CFD-based modeling and simulation of the loose abrasive-based method.

References	Work-Piece Material	Type of Abrasive-Based Process	Important Input and Output Variable Considered	Software Tool	Remarks
[119]	hard materials	Magnetic field-assisted finishing (MFAF)	Continuity and momentum	-	The active abrasive grain axial force is higher than the force of the reaction due to the strength of the material. CFD is an effective tool for predicting the surface roughness in abrasive flow-based machining.
[120]	Silicon carbide	Abrasive flow machining (AFM)	Shear modulus, elastic modulus, damping factor, stiffness	ANSYS CFX	CFD is an effective tool for predicting the surface roughness in abrasive flow-based machining.
[100]	-	Abrasive flow machining (AFM)	“Density, the extrusion pressure, piston velocity, abrasive hardness, particle hardness and media viscosity, workpiece hardness.”	ANSYS FLUENT	The process was a precision finishing operation. Therefore, the removed material is low. This amount can be increased with the increase in the number of cycles. The modeling and the simulation are very important due to the high number of parameters

References	Work-Piece Material	Type of Abrasive-Based Process	Important Input and Output Variable Considered	Software Tool	Remarks
[106]	**Visco-elastic materials**	**"Ultrasonic assisted abrasive flow machining (UAAFM)"**	**"Fluid pressure, the velocity profile of the fluid, temperature distribution in the working fluid, wall shear, angle of impact, and finishing rate"**	**Commercial simulation tool for CFD**	**The impact angle 'θ' plays a major role in the machining process and improves effectiveness. Wall shear helps predict if the process has better finishing rates.**
[121]	**Turbine blades**	**Abrasive wear**	**Size and shape of quartz particles, leakage flow through clearance gaps, blade life, and efficiency.**		**When compared with the data from the actual erosion in turbines, the CFD results give more information. The leakage flow through clearance gaps of guide vanes causes erosion in the runner blade inlet.**

Even though the CFD simulation model has the edge over other processing models, a lot of advancement has occurred in other simulation models. The finite element method-based simulation model is one of them. The next section describes the significance of FEM simulation-based processes.

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