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ORIGINAL ARTICLE

State-of-the-art on vibratory finishing in the aviation industry: an industrial and academic perspective

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Abstract Vibratory finishing is a versatile process that is used in many industries globally for radiusing, brightening, deburring, fine finishing, cleaning, burnishing, and descaling of components. This state-of-the-art paper will discuss how vibratory finishing has evolved into what it is today and the advancements in technology. The development of mass finishing, the importance of vibratory finishing in aviation industry, the parameters involved in this process, and the patent landscape of the advancements in vibratory finishing will be elucidated. More importantly, the paper will dwell into attempts made to understand the science behind this arcane process. Empirical investigations, model developments, bulk and granular impact velocity studies, vibrostrengthening, and Almen strip characterization are the research efforts that will be discussed in particular. This work has identified gaps in the vibratory finishing process, some of them being media flow measurement and the need for a monitoring system to determine the frequency losses from motor vibrations to the media vibrations. Methods for calculating the frequency and amplitude of machine vibrations, the impact velocity of media, and the force of media striking the workpiece are still under research. Literature points out that more work can be done in terms of the quantification of process parameters, the relationship between them, and the effect they have on the surface finish. The industry is on the lookout for shorter cycle times with improved surface finishing quality, and thus various technological advancements in vibratory finishing, namely drag and spindle finishing, have come into existence. To the knowledge of the authors, there has been no comprehensive review work done on vibratory finishing. This paper attempts to serve the purpose of being a one-stop academic and industrial reference for scientific communities and professionals working in this field. The paper further endeavors to serve as a means to initiate the development of a next generation vibratory finishing system with real-time monitoring and surface finish measurements.

Keywords Vibratory finishing · Short cycle time · Eccentric weights · Media motion · Model development · Fixturing

1 Introduction

Vibratory finishing has become increasingly significant over the last decades in the value chain of product development in a variety of industries especially aviation. This is due to enhanced automation of the process as well as due to the many different process engineering applications of modern vibratory finishing technology. Yabuki et al. adequately summed up the versatility of the process in one line: it can be aggressive enough for removal of burrs in steel parts as well as sufficiently delicate to polish plastics [1].

Vibratory finishing is a process under the broad umbrella of mass finishing. Mass finishing consists of abrasive industrial processes by which a substantial quantity of components made from metal or other materials can be economically processed in bulk to achieve one or several of a variety of surface effects such as deburring, edge radiusing, brightening,

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removing surface roughness, and stress relieving among others [2]. With such a wide variety of applications, the processes are used extensively by the manufacturing industries. The inherent economy, flexibility, and adaptability of mass finishing systems have made them unique methods for improvement of a vast variety of industrial parts. The consequences of not performing mass finishing processes can be quite severe: parts will perform poorly due to decreased load capacity, poor corrosion, and fatigue resistance to name a few.

This paper gives an overview of the mass finishing processes, how mass finishing has evolved over the years, and focuses mainly on the machines and machine characteristics that bring about the surface finish particularly for the vibratory finishing process. The key process variables for vibratory finishing, its importance in the aviation industry, and technological advancements particularly to do with lowering the long cycle times in such a process and the efforts that have been made so far to understand this empirical process will also be discussed briefly.

2 Mass finishing and its historical development

Mass finishing is a general term for abrasive industrial processes, with loose particles known as media, together with compound, all within a container in which components are submerged. Barrel finishing, vibratory finishing, centrifugal finishing, and drag finishing are such processes included within broad purview of mass finishing. Energy is imparted to this abrasive media by a variety of vibratory-cyclical motions to cause it to interact with part surfaces. To date, vibratory finishing is the most widely known mass finishing process.

Mass finishing processes established their place in the industry in the 1900s. Barrel finishing is said to be the original mass finishing method. The first demonstration of mass finishing process was tumbling barrels with natural stones used by ancient Chinese and Egyptians to polish their weapons and jewelry [3]. Mass finishing processes have evolved in technology and innovation. This has resulted in many variants—barrel finishing, vibratory finishing, centrifugal finishing, and drag finishing. Although the key process variables (KPVs) of any mass finishing setup vary from process to process, they can be classified under four broad headings as shown in Fig. 1. Since these four KPVs—media, compound, machine, and workpiece—are highly interdependent, they can be visualized as a tetrahedron called the "Tetrahedron of Interdependence" [4].

The functions of the various process parameters are as follows [4, 5]:

1. Media: Media is the main element responsible for imparting the necessary surface finish to the components. It can be abrasive as well non-abrasive.

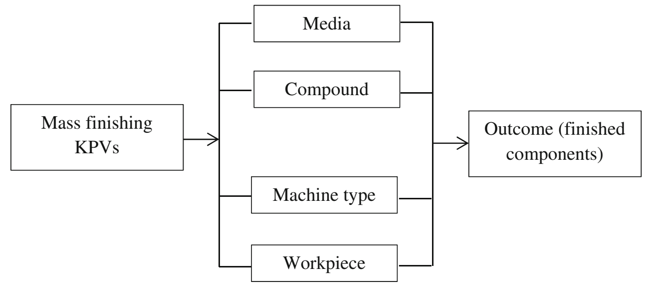

Fig. 1 Mass finishing KPVs

2. Compound: Compound is the water-based lubricant and coolant in the process. It has a lot of uses—draining abraded material, cleaning the surface to be finished, and controlling the pH of the process among others.
3. Machine type: Mass finishing machines have evolved since the inception of the process. From barrels to drag finishers, there has been a continuous evolution of technology and efficiency. Different machines differ in their finishing actions and the media motion inside the machine.
4. Workpiece: Workpiece is the most important of the process variables. The workpiece dictates all of the above parameters. For example, the size and material of the components to be processed dictate the type of the machine and media. A large component undergoing polishing will have to be finished in a big machine with a suitable polishing or non-abrasive media and compound.

The factors inherent to the mass finishing process—media, compound, and machine type have witnessed many improvements since the industrial deployment of mass finishing. The most significant have been in terms of the machine type. This evolution of technology is shown in Fig. 2.

3 Vibratory finishing in the aviation industry

Davidson [7] duly summarized why edge and surface conditioning is critical: "Sometimes, to fully understand the significance of edge and surface quality issues, it is important to understand the magnitude of the consequences when edge and surface condition receive insufficient attention." The end-products of the aviation industry operate with human life on a daily basis and thus there are stringent requirements on edge and surface conditions when it comes to the processes involved in the industry.

The aerospace industry demands very fine surface finish requirements for parts such as fan and turbine blades. If the fan blades have smooth surfaces, the risk of deposits sticking to the airfoil surface is reduced. The smoother the airfoil surfaces, the lower the engine operating temperatures. This allows a greater margin to be achieved between the actual exhaust gas

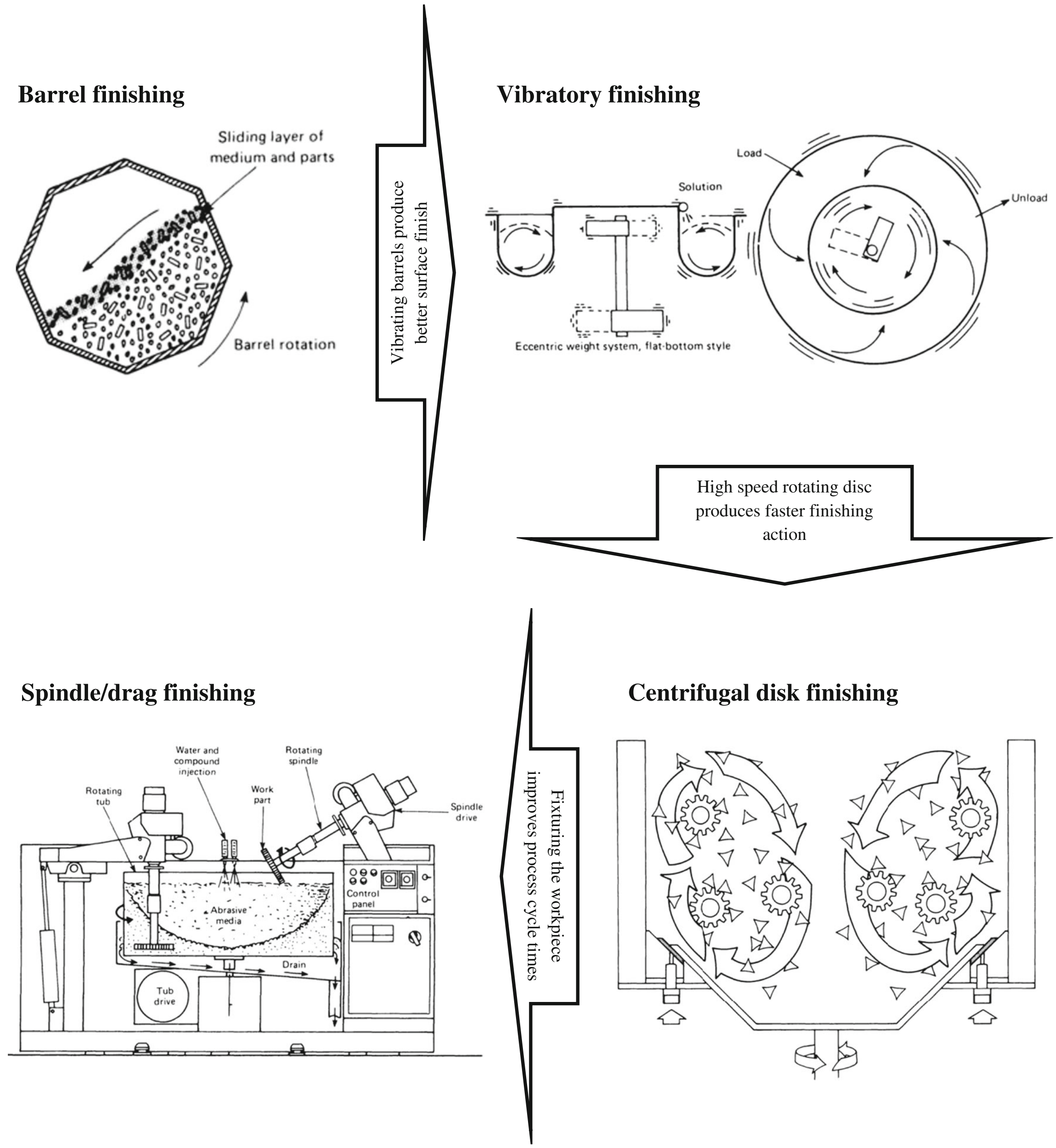

Fig. 2 Evolution of mass finishing technology [5, 6]

temperature and the engine "red line"—maximum exhaust gas temperature (MEGT) as shown in Fig. 3. This temperature reduction improves the time between overhaul for aircraft engines—they can remain in service longer before an overhaul is needed [8]. Improved surface finishing of turbine blades also enhances the acceleration and compression of the air mass flow in turbines, resulting in lower fuel consumption—an invaluable technical benefit with rising costs of fuels nowadays [9]. Lowering surface roughness also helps in increasing fatigue life [7]. This is important as the airplane components are subject to varying amount of stresses during operation.

The stress concentration in components like fan blades or turbine blades in an aircraft engine is increased by sharp corners as well as burrs. Deburring and edge radiusing reduces stress concentration, which further increases fracture resistance and fatigue life. It has been observed that most fatigue cracks are initiated at the surface of a part rather than internally. Hence, surface conditioning becomes critical for the long and safe life of a part, especially in the aerospace industry. During assembly, rough surfaces and sharp exterior edges can also damage coated or painted surfaces. Sharp outside corners on a structure act as electrical charge accumulators and can be a static discharge hazard. During flight operation, sharp edges may have an imbalance of electric charges and can become spark over points whenever voltage is applied. This potential difference can be caused by static charge and/or lightning strikes [7].

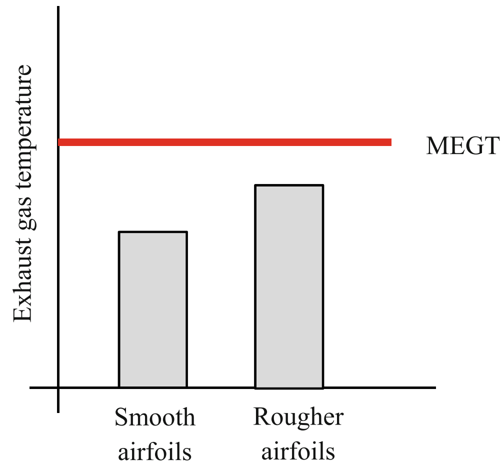

Fig. 3 The effect of surface finish on aircraft engine exhaust gas temperatures

Vibratory finishing is one such widely used process which can result in attaining the surface finish requirements specified by the aviation authorities as well as conditioning the parts to counter the potential disasters caused by the phenomena described above. The process is flexible and cost effective in terms of numerous parts with complex geometry (which is usually the case with aerospace parts) can be finished simultaneously with minimal effort in process planning. Vibratory finishing helps develop beneficial compressive stresses as well provide a stress equilibrium enhancement throughout the part, as all part features are processed identically. These compressive stresses will counteract the tensile stress caused by a crack and help to contain its propagation. Many machining and grinding processes tend to develop residual tensile stresses in the surface area of parts. These residual tensile stresses make parts susceptible to premature fracture and failure when repeatedly stressed. Vibratory finishing counters this by imparting residual compressive stresses [7]. However, vibratory finishing requires long cycle times associated with such a process. The lack of science and understanding of the mechanism behind the vibratory finishing process is a barrier to optimizing the process to its full potential.

In component applications, a typical fan blade in the aerospace industry has a length of 1,200 mm and a width of 500 mm. A tub vibrator is used to finish these blades. Smaller and rotatory aerospace components such as turbine blades, blisks, and compressor discs are finished in a vibratory bowl. During the finishing process, fixtures are used to mount these components to prevent any damage from nicking or other impingements on delicate edges [10]. The role of fixturing will be elaborated further in Sections 4.2 and 6.4. The airplane's structural fuselage components and wing spars undergo deburring and radiusing in bigger tub vibrators. Parts that are deburred and have smooth radii in contrast to sharp edges have higher resistance to fatigue crack initiation and propagation. Paint adhesion on part edges is improved as well, which is useful for downstream manufacturing processes [8, 10].

4 Vibratory finishing KPVs

Vibratory finishing is a complex process where each and every operating parameter plays a crucial role in bringing out the desired surface finish. Vibratory finishing machines come in two major configurations—the bowl and the trough. These two configurations address the variations in the size and volume of components to be finished—from huge components like fan blades to small components like turbine blades. The KPVs are the same irrespective of the machine. Each key process variable is interdependent and one cannot be ignored over the rest in bringing about the required surface finish. As mentioned in Section 1, the Tetrahedron of Interdependence will always be intertwined for any mass finishing process to obtain the finished product.

Depending on the type of component, its desired output, and potential application, the KPVs can be ranked sequentially. Though frequency of the vibratory motor is the most important parameter while selection of media is the next as the frequency of vibrations from the motor are transmitted to the media which provide the main finishing action to the component, other aspects such as the right amount of dosing of the compound for lubrication and cleaning apart from other machine parameters are also vital. These parameters are listed in Fig. 4.

The literature review on the key aspects of the machine characteristics is summarized in Fig. 5. The motor and the eccentric weights collectively are referred to as the 'unbalanced mass drive system' and is the core of the vibratory finishing process. Sections 4.1 and 4.2 will elaborate more on the unbalanced drive system and fixturing.

4.1 Motor and eccentric weights

At the heart of the vibratory finishing process is a motor with eccentric weights, hence the name "unbalanced mass drive system". It is attached to the bowl or the tub which is fixed to the ground by means of springs. Eccentric weights are attached to the ends of the motor shaft which causes wobbling action when it rotates, which in turn vibrates the assembly. The frequency is usually controlled by specifying the speed of the motor. The amplitude and direction of rotation are changed by modifying the eccentric weights attached to the motor. These are referred to as the input parameters of the process in addition to the type of compound and media. Typical ranges for frequency and amplitude are 20–60 Hz and 2–10 mm, respectively [5].

High-speed motors are also being implemented to reduce cycle times [11, 12]. The speed of the motor designed in [11] was up to 40 Hz as compared to between 20 to 25 Hz operating in similar machines and the time taken to reach roughness saturation reduced by approximately 40 %. In both the references [11, 12], there is a consensus on the faster and uniform rotational movement of the media in a high-speed vibratory finishing

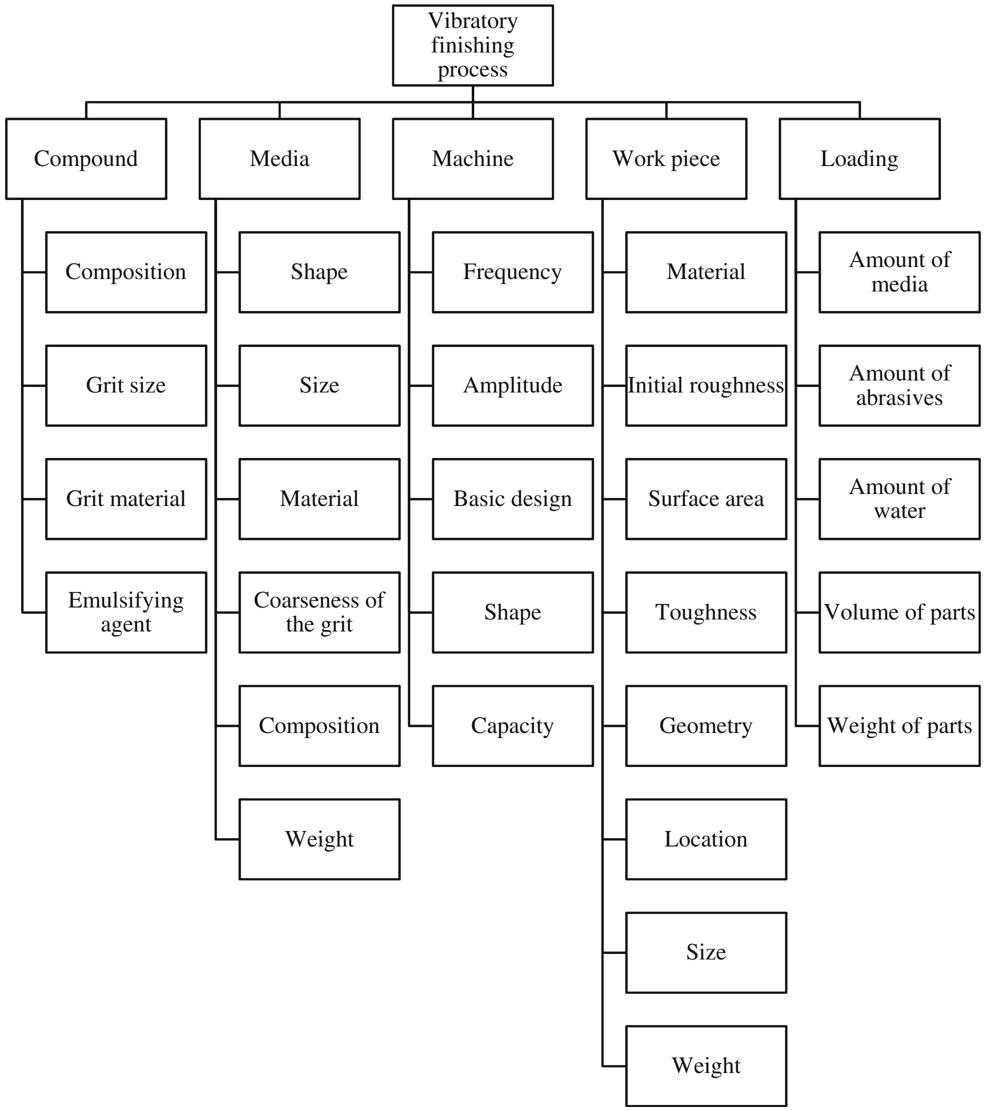

Fig. 4 Vibratory finishing KPVs [3]

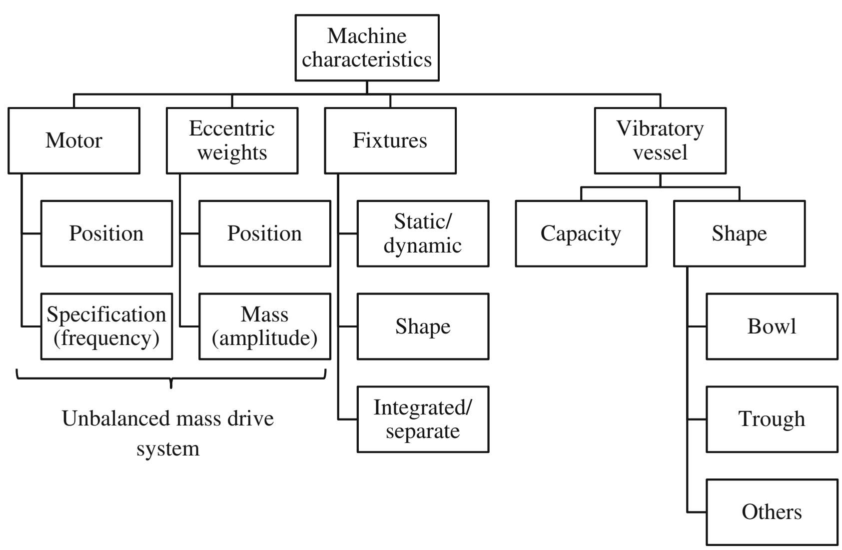

Fig. 5 Vibratory finishing machine characteristics

machine in comparison to a conventional one. However, there have been contrasting observations made pertaining to media's amplitude of vibrations. In the machine designed in reference [11], the amplitude of media vibrations reduces at higher speeds and the media maintains a much more consistent contact time with the component. These result in lower surface impingements and a more homogeneous surface finish on the entire surface of the components in a shorter cycle time. Rawlinson [12] attributes faster cycle times to uniform and increased media speed and a precise control of high amplitude of vibrations. Further research can be conducted to ascertain which level of amplitude—low or high—is responsible for faster finishing at high frequency of vibrations. Changes in eccentric weights to alter the amplitude will play a crucial role in understanding the role of high/low amplitudes in a high-frequency machine.

For a vibratory bowl, the motion of the workload in the machine is considered as helical. There are two types of motions—"roll"motion in which media rises at the outer diameter wall and falls down toward the center hub and the "feed" motion in which the workload travels clockwise or counterclockwise lapping path around the bowl channel as illustrated in Fig. 6 by Domblesky et al. [13]. Roll motion is determined by the mass of the lower eccentric weight, whereas feed motion is determined by the mass of the upper eccentric weight. By convention, the bottom eccentric weight always leads the top weight in the direction of rotation of the drive shaft, whereas the media always rotates in the direction opposite to the drive shaft rotation. The angle between the two eccentric weights, known as the lead angle, controls both roll and feed motions [5]. This concept is well illustrated by Nebiolo [14] and is shown in Fig. 7.

For a vibratory trough, the method of inducing vibrations is the same as in vibratory bowls. The motion is simpler—it is rotatory as shown in a cross section of a trough in Fig. 8 [3].

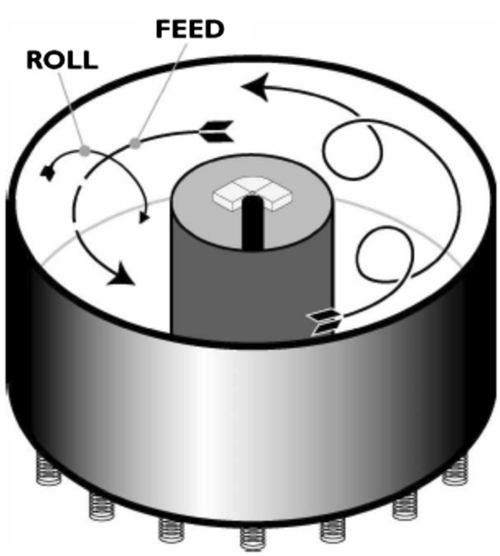

Fig. 6 Roll and feed motions in a vibratory bowl [13]

4.2 Fixtures—an upcoming trend

There has been limited research work in the literature with respect to immobilization of the workpieces by deploying fixtures which offers another research approach. [15, 16]. For high-value components such as turbine blades, it becomes important to immobilize the workpieces to prevent them from colliding into one another. The other advantages of fixturing include faster cycle times, finer surface finishes, and prevention of damage to the bowl liner from the sharp edges of parts [3].

Fixturing of components is rather a relatively new concept in the field of vibratory finishing, where the component is held by suitable means and immersed into the media container. This type of fixtured vibratory finishing is also referred to as vibrostrengthening [16]. These fixtures can be static (fixed on the vibratory setup) or dynamic (freely floating). Both the configurations are known to speed up the finishing process producing desired R_a values in lesser cycle times. This is because the force flow of media against the components is said to increase considerably and there is an increase in the relative velocities between the media and the workpiece [15–17].

In a way, drag finishing, spindle finishing, and stream finishing are advanced forms of fixtured finishing. In both these methods, the parts that are to be finished are clamped by suitable means. These methods are known to reduce cycle times by almost 33 % compared to conventional vibratory finishing [5].

5 Patent analysis

A thorough patent search related to vibratory finishing was also carried out in this work in order to determine the innovations that have come about pertaining to the various KPVs of vibratory finishing. A general trend that was observed was that most of the patents dealt with improving the vibratory finishing process in terms of improving cycle times and producing quality surface finish.

Going along the lines of high-speed vibratory motors reducing cycle times discussed in Section 4.1, Hammond Machinery [18] patented a high-speed mass finishing system with special arrangement of the eccentric weights and increased horse power of the motor causing the spinning shaft to rotate at 2,000 rpm or more [11]. Innovative fixturing methods have got their fair share of patents as well. Van Kleef and Sothorn in their patent [19] refer to a spindle fixturing method along with mixing of media through means of a plate which can be lifted up or down vertically through the abrasive media. Walther Trowal's patent in 2012 [20] is to do with electromagnetic means of fixturing ferromagnetic workpieces. A patent on magnetic fixture by REM technologies [21] and vibratory fixture by MERMARK INC. [22] are other patents to do with

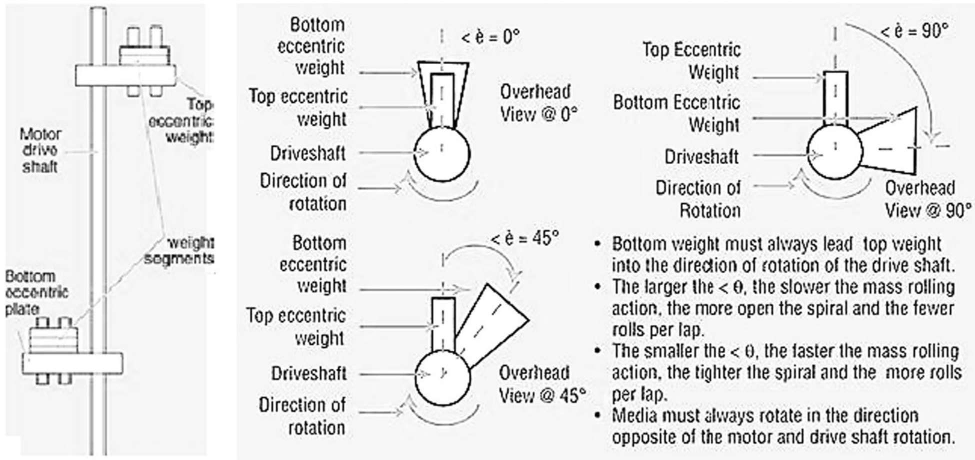

Fig. 7 Eccentric weights in a vibratory bowl [14]

fixturing. Rolls-Royce Deutschland's patent deals with strengthening elements (media) and the shape for these elements. REM technologies have also patented the chemically accelerated finishing process [23]. Apart from this, patents pertaining to the use of dividers and means for separating parts from media for faster process times were also seen.

Based on the patent search that was conducted, the authors came up with the patent map as shown in Fig. 9. The patent map clearly establishes that most of the patents pertain to the unbalanced mass drive system and special means of fixturing the workpieces in order to reduce cycle times. Patents related to other operating parameters such as media, compound, and separation means of media from the components were also seen in the patent search conducted iterating the fact that vibratory finishing is a process which involves multiple parameters and one parameter cannot be ignored over the other in order to bring about the optimal surface finish.

6 Research efforts in vibratory finishing

To date, vibratory finishing investigations are largely based on trial and error in order to determine the optimal parameters to bring about the desired surface finish of a component [3, 9, 13, 24–28]. The mechanism behind vibratory finishing still remains unclear in spite of various studies that have been conducted. The main research areas are shown in Fig. 10. This section discusses the main findings from these research studies briefly. These can be applied by personnel operating vibratory finishing machines such as in the aviation industry and scientists working on the process in order to better understand and optimize their processes and experiments, respectively.

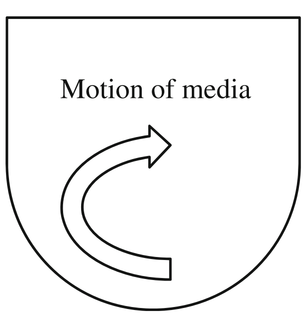

Fig. 8 Media motion in a cross section of a vibratory trough

6.1 Empirical investigations

Doody [29] mentioned in his research on microprocessor-control techniques for vibratory finishing that the characteristics of vibratory energy transferred to the processing media depends on: rotation speed of the motor shaft, relative positions of the eccentric masses, total eccentric mass fitted to the shaft, and the radial distance between the centers of top and bottom masses. This can be related to the discussion in Section 4.1 on motors and eccentric weights. The change in vibratory characteristics can be observed in a vibratory finishing machine by simply increasing the speed of the motor or modifying the configuration of eccentric weights. Increasing the frequency of vibrations of the machine can be accomplished by increasing the motor speed on the control panel of the vibratory machine. The amplitude of vibrations can be altered by changing the weights/orientation of the weights on the vibratory motor. Most conventional vibratory machines come with an amplitude label attached on them from which the amplitude of vibrations can be determined. This method is not a very robust one and is based on visual inspection of the label. The amplitude resolution of 0.5 mm is used within an operating window of 2 to 8 mm. A more comprehensive displacement sensor or amplitude meter needs to be devised to increase the reliability of amplitude measurements. Studies on the effect of media amplitude on vibratory finishing are limited. Precise monitoring of amplitude is required to investigate the effect of different levels of amplitude on the finishing process.

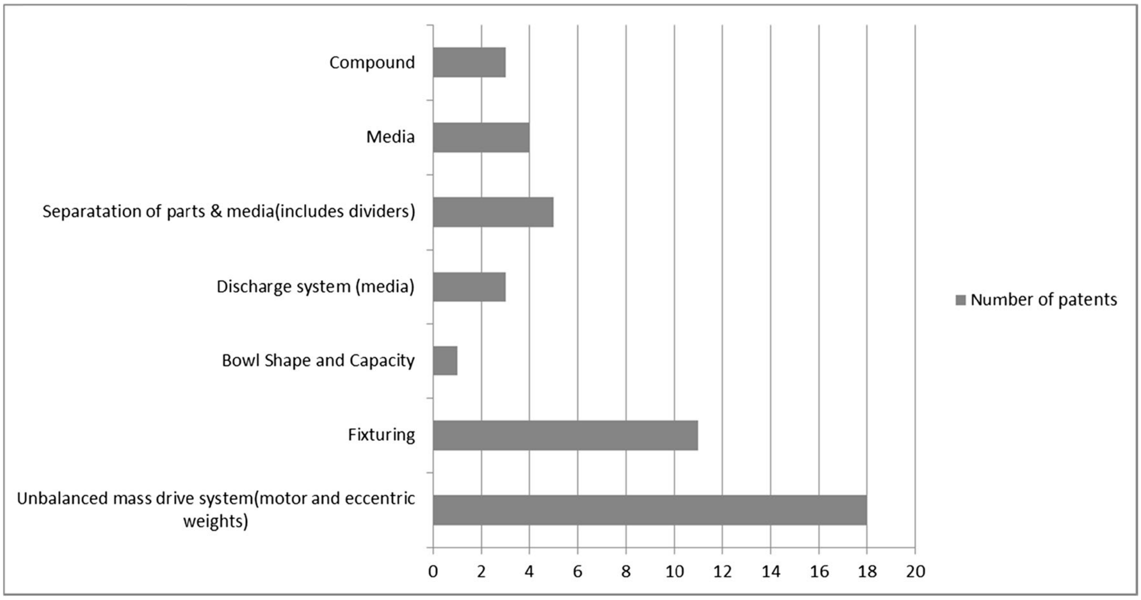

Fig. 9 Patent map

Wang et al. [25] devised a special load cell to measure normal contact forces between the media and the workpiece in a vibratory bowl finisher. Fourier transform of force signals exhibited that most of the energy occurred at the same operating frequency of the finisher. This means that most of the force transferred from media to the component occurred at the machine's operating frequency. Comparable results were obtained when the sensor was placed facing forward as well as backward in the workpiece spiraling around the bowl. It was concluded that impact wear conditions were relatively constant against all of the workpiece surfaces. Fixed workpiece trials were also carried out and it was observed that contact forces were greater in this configuration as compared to a freely moving workpiece in the media. This goes in tandem with the concept of fixturing as discussed in Section 4.2.

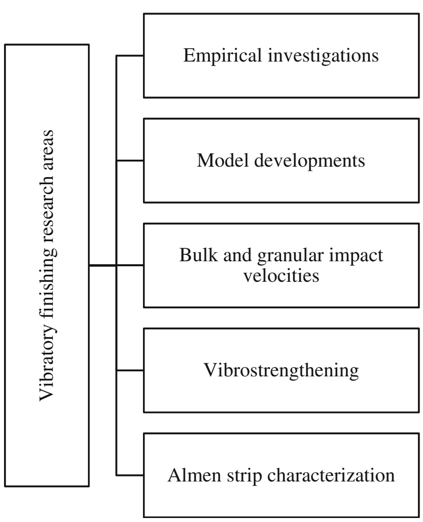

Fig. 10 Vibratory finishing research areas

Fixturing has thus become increasingly emphasized in vibratory finishing as cycle times are considerably reduced. An increasing trend of average impact forces and the average impulse with increasing media size was observed for dry conditions, but not significantly for wet conditions. Wang et al. also observed that as the amount of lubrication increases from dry to water-wet to detergent-wet, both the absolute workpiece speed and the speed of the media relative to the workpiece decreases, and hence, concluded that lubrication condition has a greater relative effect on the speed of the media than that of the workpiece. The hardness and roughness changes were mostly influenced by the degree of lubrication, the media size and its roughness. This is because the plastic deformation per impact is affected by the interaction between the media and the workpiece [25]. Parameters such as lubrication (type and quantity) through a suitable compound and media properties cannot be ignored to bring about the required surface finish on components, thereby reinforcing the Tetrahedron of Interdependence.

Yabuki et al. [1] devised a new force sensor to measure normal and tangential contact forces of media in vibratory bowl. They also videotaped media contact modes. The schematics of the three contact modes—free impact, rolling of individual media, and adjacent media rolling over a stationary piece of media—are shown in Fig. 11. Scanning electron micrographs and force sensor measurements showed that a free impact (Fig. 11a) produced a relatively small crater and force signal; rolling of individual media (Fig. 11b) produced a track of small craters and a force signal burst with multiple distinct peaks separated by complete unloading and adjacent media rolling over a stationary media (Fig. 11c) produced the largest single crater and a force burst with a higher average contact force and incomplete unloading [1]. A key finding is that the

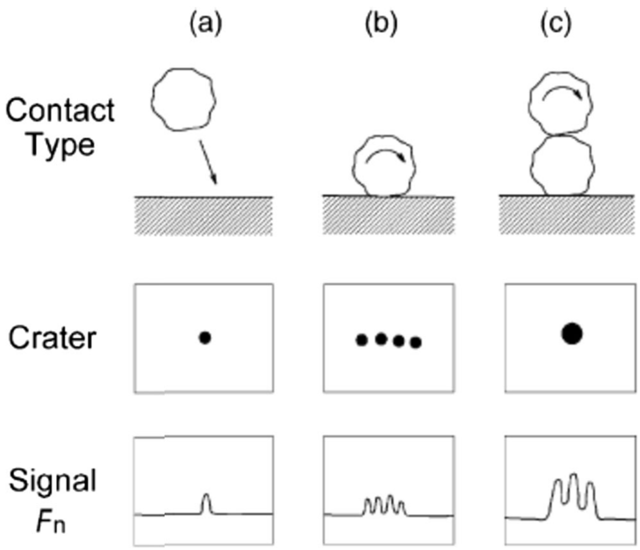

Fig. 11 Contact modes of media in vibratory finishing: **a** free impact, **b** rolling of individual media, and **c** adjacent media rolling over a stationary piece of media [1]

component should be mounted in a fixture in a way that it is in the direction of media flow for the greatest impact and faster finishing. It was also observed that in the dry condition, the maximum impact force and frequency of impact occurrence were much higher than in the water-wet condition. The following factors were stated as the causes of the above observation that was rendered unexplainable by Wang et al. [25]: (i) reduced coefficient of friction in the finisher due to water wetting and hence lower energy transfer efficiency from the wall to the media; (ii) a water film on the media promotes adhesion and acts to dissipate impact energy; and (iii) increased lubrication reduced the speed of media relative to workpiece. It can therefore be concluded though lubrication aids in the vibratory finishing process, excess lubricant can reduce the speed of media impact and increase finishing time.

Baghbanan et al. [30] experimented with the same force sensor as developed by Yabuki et al. [1] in a vibratory finishing trough. It was observed that the pattern of normal and tangential forces and the surface property changes in a trough finisher were similar to that in a bowl finisher observed by Wang et al. [25] and Yabuki et al. [1]. The relationship between hardness and finishing time was also reported to be similar for the small, low energy bowl finisher and the large, high-energy trough. However, a different mounting method for the workpieces in the trough—clamping instead of adhesive bonding that was used in case of the bowl—was attributed for minor variations of the results. Lubrication condition was also experimented with and it was found that it significantly affected the workpiece hardness and surface roughness [30] similar to the observations made by Wang et al. [25] and Yabuki et al. [1] Hence, it was concluded that vibratory finishing follows a general pattern that is irrespective of the type of machine, vibration frequency and amplitude. Similar conditions of vibratory finishing are seen across the different types of vibratory equipment- be it a bowl or trough type. Fixtures are used in both the configurations; however the design of the fixture will depend on the component being finished. One significant difference between the bowl and the trough that was characterized through Almen strips was higher impact energy of media in the tub. This can be explained by the fact that the machines were operated at different frequencies—30 Hz for the bowl and 47 Hz for the tub. Higher impact energies with increasing frequency may also explain the reduced cycle times with high-speed motors discussed in Section 4.1.

Domblesky et al. [13] conducted experiments with the vibratory bowl finisher and investigated the changes in material removal rate and surface finish of workpiece materials—aluminum, brass, and steel as a function of media, workpiece material, bowl acceleration, and finishing duration. It was mentioned that abrasive wear and grinding are fundamentally related to mass finishing from a material removal perspective. This is because in both processes, minute asperities abrade material from a workpiece surface by scratching the surface on a microscopic scale. In the experiments carried out, Domblesky et al. hypothesized that based on their respective mechanical properties, aluminum would have the maximum material removal rate and steel the lowest. It was observed that brass had the highest material removal rate (MRR) and aluminum the lowest. This observation was attributed to the similar densities of the media and aluminum which would result in lower relative motion between the two. Further investigations were called for to comprehend the reason behind the MRR of brass being twice that of steel. It was noted in the experiments that the resultant bowl acceleration is highly affected by the total roll weight (bottom eccentric weight) as compared to the feed weight (upper eccentric weight). This observation builds on the role of roll and feed weights as discussed in Section 4.1. It was suggested that for deburring and edge radiusing applications, roll setting should be used as the primary means to control and optimize cutting action and MRR. This suggestion is useful for personnel involved in deburring and edge radiusing of aerospace components through vibratory finishing. One potential limitation that the authors of this State-of-the-Art study note is that whether the suggestions made by Domblesky et al. can be implemented in other vibratory bowls since different machines come with varying configurations of eccentric weights. MRR was found to be directly related to the resultant bowl acceleration and the difference in density between media and workpieces [13]. MRR also differs from material to material, but for a given material, it was constant over time. Workpiece hardness was also found to be a factor in influencing material removal rate with softer workpieces having higher material removal rates.

Kumar et al. [28] devised a simple 1D simulator for the vibratory finishing process. Titanium workpieces were tested for material removal rates, surface roughness and contact forces were measured in two different arrangements. Through experimental investigations, it was found that surfaces which are placed deeper in the media and perpendicular to the vibratory motion demonstrated higher MRRs. Media flow can be visualized as layers—media deeper in the container move with the weight of media layers above it and hence strike the component with a different force than a media layer on the surface, thereby causing higher material removal. Modeling of contact forces of the media and workpiece was carried out using multibody dynamics simulation. While it proved to be a suitable method, Kumar et al. state that it must be optimized further to be used along with a prediction model. More accurate predictions of peak contact forces and other relatively small forces need to be done in order to render the simulation results useful for material removal prediction of the workpiece.

6.2 Vibratory finishing process—model developments

Sofronas et al. [31] were one of the earliest researchers to develop a comprehensive model for vibratory finishing process in 1979. They used a statistical tool known as response surface methodology to investigate the effect of hardness, projection width, processing time, media size, and vibration frequencies on workpiece projection height reduction, edge radiusing, and surface finish reduction [31]. These three dependent variables are well illustrated in Fig. 12. It was noted that the reduction in height of projections was accomplished by a "hammering" or "peening" action with a subsequent plastic deformation in bending. It was also claimed that a similar mechanism was responsible for the radiusing and surface finish reduction as opposed to an abrasive metal removal mechanism. It was concluded from experiments that the vibratory frequency was the most significant process variable with higher frequencies increasing the responses of the dependent variables illustrated in Fig. 12, followed by media size and processing time. The implementation of high-speed motors to reduce cycle times as discussed in Section 4.1 are in accordance with the findings from this study by Sofronas.

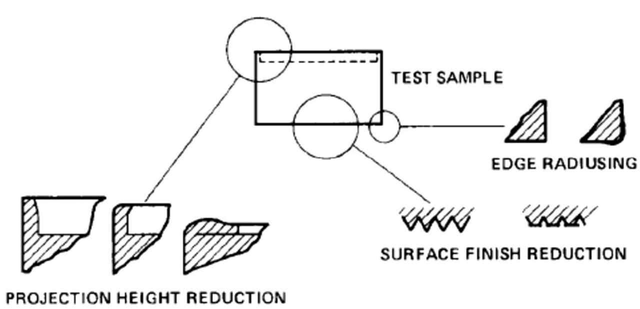

Fig. 12 Projection height reduction, surface finish reduction, and edge radiusing in a workpiece [31]

Hashimoto [24] followed suit and established fundamental principles of the vibratory finishing process and proposed mathematical models using differential equations for predicting surface roughness and stock removal. Three rules were proposed for the vibratory finishing process based on the experimental results obtained. First, the roughness of the workpieces subject to vibratory finishing will exponentially decline to a constant value known as "roughness limitation," which is dependent on the inherent surface texture of the workpiece. Second, the higher the difference between the roughness of workpiece and its roughness limitation, the faster the roughness changes of the workpiece. Lastly, Hashimoto proposed that in the steady state, the vibratory finishing process has a constant stock removal rate. He used two bowl vibrators with varying capacity, frequency of 21 Hz, and amplitude of 5 mm for his experiments. Hashimoto's experimental results matched well with the predictions of his mathematical models. The proposed rules are universally observed in a vibratory finishing setup and the vibratory finishing operators can use the models proposed to optimize the process cycle times as well. The rules can be extended to machines with high-speed motors that are available in the industry today as similar saturation curves were observed in [11].

Domblesky et al. [26] followed up their experimental investigation of vibratory bowl finishing [13] and proposed a material removal model using cutting forces as the starting point for the model development. The model was validated with experiments and it was established that MRR is time independent, reinforcing Hashimoto's [24] third rule. Although the results appeared to support the proposed MRR model, further work can be done to affirm the effect of different media and workpiece mass on MRR. The authors of present State-of-the-Art study opine that Domblesky et al. made certain simplifying assumptions for the development of their model. Firstly, the peening mechanism proposed by Sofronas et al. [31] was neglected as it was claimed that that would not influence the rate of material removal. It was observed that MRR is proportional to bowl acceleration, indicating an aggressive cutting action at high acceleration levels. It was further implied that high acceleration should reduce cycle times for edge radiusing applications where a high level of material removal is needed. This contradicts the peening and plastic deformation mechanism explained by Sofronas et al. [31] for edge radiusing. Secondly, media was assumed to be self-sharpening and the cutting action was insignificant over time. However, in actual processes, media is influenced over time and a suitable assumption for the change of media could have been implemented. These observations and contradictions made can be corrected and implemented for further research on understanding vibratory finishing.

Naeini et al. [32] took modeling to the next step and developed a discrete element model (DEM) to simulate bulk spherical steel media flow in a 2D vibrationally fluidized system.

DEM is used to simulate the collisions and subsequent velocities of the media, container, and workpiece. The DE model employed a linear contact model with contact parameters as follows: normal and tangential stiffness (k), normal and tangential damping (β), and sliding friction (μ). It was highlighted that further improvements in the model predictions can be made by treating normal and tangential stiffness and damping parameters as distinct rather than equal as done by Naeini et al. The extent of plastic deformation and erosion of the workpiece surface is controlled by the media impact forces which in turn are controlled by the media impact velocities. The DEM predicted that normal contact velocity components were six to eight times larger than the tangential components. Experimentally, it was found that the normal contact forces between media and sensor were approximately ten times higher than tangential forces [1, 32]. This paper combines the mechanisms proposed by Domblesky et al. (abrasive material removal) [26] and Sofronas et al. (peening) [31] and attributes it to normal impact forces and velocities of the media. The authors of the present State-of-the-Art study concur with Naeini et al. in that vibratory finishing has dual mechanisms operating to give the necessary surface condition: plastic deformation by media impacts and material removal by relative motion of media and workpiece.

Naeini et al. [33] modelled the development of single-cell bulk circulation of two different media in vibratory beds using a 2D discrete element method. The bed of spherical particles was modeled as a single layer of disk with the assumption that all collisions and motion occurred in the x–y plane. The vital difference between this study [33] and that done by the same authors in [32] was the spacing of glass partition plates used to hold media in the vibratory troughs. In the previous experiment [32], the glass plates were spaced to accommodate only a single layer of particles as compared to a spacing of 100 mm in the present setup, which led to the media flow having a greater 3D component. Naeini et al. wanted to determine to what extent the 2D DEM can represent such a nominally 2D flow. It was mention that resultant shear forces between the container walls and media were related to the behavior of the system. Model predictions were confirmed with experimental results. It was found that with greater depth of the media in the container, the magnitude of the bulk circulation increased and hence, components placed deeper in the media will be subject to harsher finishing as compared to components placed near the surface of the media. This was further substantiated by Kumar et al. [28] in 2012. Naeini et al.'s modeling attempts can be carried forward by considering how the shear forces at the finisher walls are transferred between particles into the bulk. As technology and research have evolved, more insights are being gained into vibratory finishing. The findings from Naeini et al.'s experiments will help to determine the optimal position to place the component in a vibratory finisher for best results.

Uhlmann et al. [34] investigated and developed a geometry-based model for prediction of changes in surface roughness-profile for the transient period of vibratory finishing. According to Hashimoto's rules [24], the transient period is defined as the time it takes for the initial roughness value to exponentially decline to reach the "roughness limitation" value. Uhlmann et al.'s study aimed to predict surface roughness through the formulation of the empirical process model as a quantitative method. The model was based on the hypothesis that during the transient period, the MRR is proportional to the improvement in surface roughness. The model's predictions were verified with measurements after different process times through a profilometer and it was shown that the model's predictions seemed to fit the measurements fairly well with mean residuals ranging from −0.7 to + 2.1 %. For the given process parameters, it was presented that the model could also be transferred to a workpiece with different topographical features. Systematical forecast errors in the model were found to increase with process times. It was suggested that these errors were due to the change of material removal mechanism during the transient period. Further research in underlying material removal mechanisms of vibratory finishing and on the transferability of the developed model to different workpiece shapes, initial roughness, materials, and media can be carried out. Uhlmann et al.'s observations reinforce the disadvantages of vibratory finishing highlighted in Section 3—the lack of knowledge of the exact material removal mechanisms at play in the process. Existing research has uncovered some knowledge, but an overall picture is yet to be painted.

Uhlmann et al. [27] also investigated vibratory finishing and determined a process model combining the geometric model developed in reference [34], with DEM and experimental results. Experimental investigations on vibratory and drag finishing were carried out to establish the relationship between vibratory finishing processes and process parameters such as processing time, workpiece speed, excitation frequency, abrasive media, and initial surface roughness of workpieces. Experimental results were utilized for the model developed. Transient MRRs in vibratory finishing were found to be strongly dependent on the initial surface roughness. The causes for different material removal mechanisms were stated as follows: for abrasion and micro-cutting mechanism, relative velocity between workpiece and media is the primary factor in controlling the MRR; for a predominantly cutting-like material removal mechanism, the intensity of media impact is the primary factor in controlling the MRR. Experiments for drag finishing, which is an advanced form of fixtured vibratory finishing, also showed a steady increase in surface roughness improvement for spherical media with a rise in energy input. This high-energy input is given by an increase in excitation frequency and workpiece speed. The observations provide relevant experimental evidence to the discussion of high-speed motors and fixtures in improving cycle times as mentioned in Sections 4.1 and 4.2.

6.3 Bulk and granular impact velocities

Ciampini et al. [35] measured surface-normal impact velocity distributions, frequencies of impact and impact power per unit area using a piezoelectric impact force sensor. The work was an extension of Wang et al. [25] and Yabuki et al. [1] in terms of developing a method to extract normal impact velocity from the impact force signals. One notable difference from earlier studies was that the sensor was fixed as opposed to freely flowing with the media. This fixed support provided impact velocity data that was independent of the workpiece size, shape, and material. Porcelain and steel spheres were dropped onto the sensor cap from known heights—this was used to determine the relationship between impact velocity and force signal. Two modes of contact between media and the sensor were observed—short duration direct impact contacts and longer duration non-impact contacts. The impact modes are well illustrated in Fig. 13, which showed periodically within time frames called "bursts" and the lengths of these burst periods were in correspondence with the finisher's driving frequency. It was proposed that the infrequent, high-velocity impacts may have a higher significance in the mechanics of vibratory finishing as compared to the frequent, low velocity impacts since the former is the main cause for plastic deformation and hardening of the impact site. The importance of frequent, low velocity impacts depends on the application. In one application of vibratory finishing machines—drying with nimble, absorptive media—involves light contact and hence low-velocity impacts become important as opposed to burnishing, where high-energy contacts are required to create plastic deformation. By varying the media masses, it was found that increasing the media mass had the effect of reducing the amplitude without affecting the frequency. This happened because the eccentrically weighted shaft which generates the vibratory motion of a finisher was supported by ball bearings attached to the tub. Measurements taken from the sensors showed that finishing became more aggressive as the parts move closer to a wall and on reducing the total media mass in the vibratory finishing equipment. Ciampini et al.'s study gave insights into monitoring velocities in a vibratory finishing setup and uncovered details on how impact velocities play a role in the material removal mechanism. On the vibratory finishing machine, the velocities can be altered by changing motor RPM (frequency). Combined with the results of Kumar et al. [28], more experiments can be carried to determine the best possible position for fixing a workpiece in a vibratory finisher for ideal results for various applications—finishing, drying, and burnishing among others. Ciampini only stressed on the plastic deformation mechanism in vibratory finishing. Further research can be conducted to identify if the infrequent, high-velocity impacts have an effect on material removal by measuring the weight of the samples periodically.

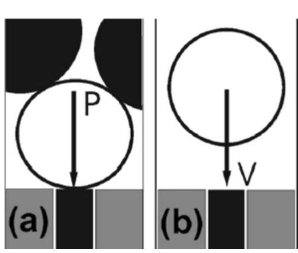

Fig. 13 Impact modes of media: **a**) longer duration non-impact contacts and **b**) short duration direct impacts [35]

Hashemnia et al. [36] refined on measuring the impact velocities of media and developed a new laser displacement probe. It was noted that the media in a vibratory finisher have two types of velocities—a large scale bulk flow velocity and a small scale impact velocity. The workpieces immersed in the media encounter repetitive, high-frequency impacts of the surrounding media. The main factors affecting the erosive wear and plastic deformation of workpieces were attributed to the velocity, frequency, and direction of the impacts of the media particles. Extreme values of impact velocities have their disadvantages—high-velocity impacts can cause fracture and fragmentation while low velocity impacts can reduce the efficiency of the process. The challenges of measuring impact velocities between vibrating particles in a vibratory finisher were highlighted—small scale of motion and difficulty in designing probes which can measure velocities on such a scale without affecting the media. The objective of the Hashemnia et al.'s study was to develop a high-speed laser displacement sensor probe to determine the surface-normal impact velocities in a vibratory finisher. The graphical methods used by Naeini et al. [32] and Wang et al. [25] to measure bulk flow properties had limited spatial resolution and hence hampered with measurements of impact velocities. The impact velocities were determined by conducting graphical analysis of the laser displacement sensor signals with MATLAB. Hashemnia et al.'s study had one experiment in consistency with the study by Ciampini et al. [35] which allowed a comparison of the sensors used—the placement of the sensors at one particular position in the trough. Ciampini et al. used impact force sensors whereas the present study involved laser displacement sensors to determine impact velocities. The present study by Hashemnia et al. [36] had velocities ranging between 50 and 100 mm/s and the previous study by Ciampini et al. [35] had velocities ranging between 0 and 20 mm/s. The most significant reason behind this difference was that in the Ciampini et al.'s study, a linear correlation was assumed between measured impact force and the impact velocity. Other reasons were difference in the size of the probes in the two studies and that "non-impact" contact events were excluded in the present study by Hashemnia et al. due to the nature of laser displacement sensor—non-contact method. It was observed that the depth in the flow influenced the impact velocities of the media particles—velocities were much higher farther away from the free surface. This can be linked with Kumar et al.'s [28] findings of higher MRRs at deeper locations within the media. In the present set of experiments, spherical media was used. It was highlighted that measurement of the bulk flow velocities for irregular shaped media will be challenging due to the variation in the average displacement signal from the laser sensors.

Hashemnia et al. [37] carried forward their earlier work [36] on impact velocities and developed a DEM to predict local impact and bulk flow velocities in a vibratory trough using high-speed laser displacement sensors. These values were then correlated to the measured values for spherical steel media. Hashemnia et al. mentioned that the link between sensitivity of particle impact velocities and the uncertainties in the contact coefficients used in DEMs was unknown. Hence the coefficients of restitution and friction corresponding to particle-particle and particle-wall interaction were included in DEM analyses. The impact and bulk flow velocities were observed to be relatively insensitive to the uncertainties in the coefficients of friction and restitution. The reason for impact velocities being greater at a deeper location was unclear, highlighting the inherent variability and unpredictability of this process as highlighted in Section 3. It was concluded that DEM was reasonably accurate in its predictions of local and bulk velocities of media in vibrationally fluidized beds with the maximum differences being 20 and 30 %, respectively.

6.4 Vibrostrengthening

Sangid et al. [16, 38] carried out two sets of work in the field of vibrostrengthening—one on experimental investigation of fixturing the workpiece and the second one on its visualization and modeling. Vibrostrengthening is a variant of the vibratory finishing process, which serves the dual purpose of imparting compressive residual stresses and improving surface finish. The process can be considered as a potential alternative to the shot peening process. In this process, the workpieces are fixed and the media acts upon them as discussed in Section 4.2. This results in aggressive mechanical working of the surface of the workpiece. It was observed that vibrostrengthening resulted in significant fatigue enhancements on machined workpieces. A sub-surface compressive residual stress produced due to plastic deformation by media action along with a better surface finish were said to improve the fatigue strength of the workpiece. As highlighted in Section 3, this fatigue enhancement is extremely beneficial for aerospace components. It was also observed that within the range of frequencies tested, higher the machine frequency and amplitude, the greater the fatigue life enhancement. A useful insight into variation of media action with depth was given, thereby correlating observations made by Kumar et al.[28]. On the one hand, the media are less packed at the top of the tub and move as individual particles. On the other hand, media are densely packed deeper in the trough due to the mass of the particles on top of them and hence they move as a single mass. This results in greater media impact on the workpiece and an increased mechanical working of the workpiece material. While testing the influence of processing conditions like media and compound on the process, it was noted that precise control is critical for compound dosing and sufficient time should be allowed between processing samples to ensure that the lubricant drains out of the system and the media dries up. Further experiments and methods would be needed for lubricant introduction, control and removal to obtain a "balance between the effectiveness of the process and wear rates of the vibrating medium" [16]. As discussed in Section 4, these experiments highlight that the vibratory finishing process is incomplete without any one of its KPVs.

In the second study by Sangid et al. [38], high-speed video recordings and computational models to predict the fatigue life were developed in order to understand the vibrostrengthening process better. A Plexiglas fixture attached to the side of the trough to observe the particle motion was used as the experimental setup. The media motion was observed to have two components: a high-frequency oscillatory trajectory that is completed per vibrational cycle of the tub and a slower drift trajectory that is observed to shift the oscillatory trajectory. Sangid et al. noted that the oscillatory trajectory was responsible for the outcome of the process and the drift motion was responsible for the redistribution of media and draining away the lubricant and workpiece remnants. It was observed that increasing the vibratory frequency resulted in the increase of media velocity, thereby leading to forceful media–workpiece interactions, beneficial higher residual stresses and also an increased fatigue life. The high-speed camera recordings helped in calculating the effective impact force between a media particle and the workpiece. The effective force was found to be 5.3 N and this was in accordance with previous calculations of approximately 4 to 6.5 N by Baghbanan et al. [30]. This force was found to be sufficient in order to induce a residual stress and cause plastic deformation within the realms of the experimental study. The computational model was developed to predict the fatigue life of a component based on experimentally measured values of residual stress profile and surface characteristics. This was primarily for shot peening applications. These two studies conducted by Sangid et al. highlight the versatility and potential of the vibratory finishing process beyond what it was originally designed for.

6.5 Almen strip characterization

Ciampini et al. [39] characterized the vibratory finishing process parameters using the Almen system. The Almen system is a well-established process that is used for the characterization of shot peening process. Standardized strips made of metal are clamped to a rigid support and bombarded with a shot peening stream. On being released from the clamp, the strips curve due to the residual stresses created by plastic deformation. This degree of curvature and its rate of change are related to the process variables of the shot peening process. Aluminum Almen strips were finished in the same vibratory trough and media as used by Ciampini et al. [35]. A vacuum holder was used in the trough to ensure that the strip remained flat, providing a constant boundary condition. Almen saturation curves for two contact conditions which were previously characterized using impact velocities in [35] were obtained. It was observed that higher plastic deformation and greater Almen strip deflection was caused by largest impact velocities and hence, the suitability of Almen strips to characterize the aggressiveness of the vibratory finishing process was established. Based on a novel normal impact simulator apparatus constructed by the authors [39], they provided further evidence that normal impacts are the dominant mechanism of vibratory finishing as observed by other researchers [32]. Ciampini et al. [40] also developed a model for the plastic deformation of Almen strips subject to vibratory finishing and to reinforce the role of Almen strips to characterize the vibratory finishing process.

7 Conclusions

Vibratory finishing has proven to be a particularly effective form of mass finishing despite the advancements that have been seen in the mass finishing industry. Today, it occupies a pivotal position in the production line of many industries and is considered a highly efficient and repeatable process with minimal usage of manpower as well as other resources.

The key issue pertaining to vibratory finishing which still plagues many researchers is got to do with solving the black box that encompasses the entire process. This entails clearly establishing the mechanism of the material removal and the relationship between process parameters and the surface finish obtained. This relationship between input and output parameters of the process is not clear due to the complexity of material removal mechanism and uncontrollable nature of the vibratory finishing process. For instance, there is limited knowledge on how changing an input parameter such as media and compound would positively or negatively impact the surface finish or material removal of the component. Thus, the design of this process for new components is still undertaken on a trial and error basis and largely depends on the expertise of suppliers and operators.

A number of analytical, empirical and numerical models have been developed with regards to the vibratory finishing process. Based on the literature reviewed in this work on vibratory finishing, the key findings are as follows:

1. Frequency of vibrations is the most important parameter in a vibratory finishing process with high frequency of vibrations leading to shorter cycle times.
2. There are two main mechanisms at play in a vibratory finishing process: plastic deformation by media impacts and material removal by relative motion of media and workpiece.
3. Fixturing the components to be finished increases the force flow and relative velocity of the media against the component, thereby decreasing cycle times. This is the reason why advancements in fixtured vibratory finishing for example spindle finishing have arisen.
4. Selection of media and the amount of compound play a critical role in bringing about the right surface finish.
5. Material removal rates for a particular material remain constant over time and are known to be higher when the component is perpendicular to and deeper in the media flow.
6. Normal forces and high-velocity impacts of media have been stipulated as the main causes of plastic deformation in a vibratory finishing process.
7. Three main contact modes of media in vibratory finishing have been observed: free impact, rolling of individual media and adjacent media rolling over a stationary piece of media.

However, quantifying the range of vibrational frequencies that is necessary to reduce cycle times considerably for a given component still remains. The right frequency with the appropriate amplitude is the key to imparting the desired surface finish. The strict regulations in the aviation industry have also made it necessary that components meet the high standards of quality and customer satisfaction. Although fixturing of components can help reduce cycle times considerably, there are chances that it damages the components and the repair time will counter the advantages gained by fixturing. A novel fixturing means which reduces cycle times considerably as well as one which does away with impingement on the component is still to be delved into. Researchers are also on the lookout for a 'smart' media that can help bring about material removal as well as surface roughness reduction simultaneously. Optimal level of media height in a container as well as the amount of compound that should be used still needs to be quantified for a given component. Most of the existing work has been carried out with spherical media of symmetrical shape. However, this is not representative of the actual process. Further work is necessary to elucidate the combinatorial effects of varied shapes of media.

Some gaps have been identified namely media flow measurement and the need for a monitoring system to study the frequency and energy losses from motor vibrations to the media vibrations. Current systems have only amplitude meters incorporated into them. Methods for calculating the frequency of vibrations, the impact velocity of media, and the force of media striking the workpiece are still under research. Existing work reported that further studies can be carried to investigate and improve the understanding of these parameters. Once thorough research is carried out on the above parameters, an object of great invention would be the next generation vibratory systems that could have monitoring systems incorporated in them to give industry operators real-time updates of the finishing conditions that their components are undergoing and alter parameters if necessary. A step-change would be to catalogue various components and the finishing requirements that are to be achieved against the parameters of vibratory finishing.

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