Magnetic field-assisted finishing processes: from bibliometric analysis to future trends

Adriel Magalhães Souza1 · Eraldo Jannone da Silva1 · Jason Ratay2 · Hitomi Yamaguchi2

Received: 14 February 2022 / Accepted: 17 June 2022 / Published online: 9 July 2022
© The Author(s), under exclusive licence to The Brazilian Society of Mechanical Sciences and Engineering 2022

Abstract
The need for ultraprecision finishing has grown, and magnetic field-assisted finishing has shown potential for overcoming some challenges. This study evaluates the scientific production and identifies future directions of magnetic field-assisted finishing based on a bibliometric analysis. Using Bibliometrix, network mapping and descriptive analysis were performed on 1558 documents related to magnetic field-assisted finishing-related research published over the past 51 years. The results of the comprehensive literature reviewed showed that the theme exhibits a rising trend of 56% in the last 10 years, being mainly conducted by Chinese, Indian, and American researchers. Different geometries and materials can be finished and which had surface roughness ranges from sub-nanometer- to micrometer-scale. Surface finishing of freeform dies and molds, optical components, and medical devices have been standing out as current process applications in tooling, aerospace, and biomedical industries. AISI 304 stainless steel was the most tested metal. Finally, potential areas of research were identified in the coming years, which could lead to new fields of application for magnetic field-assisted finishing in industry.

Keywords Bibliometrics · Magnetic field-assisted finishing · Magnetic abrasive finishing · Magnetorheological finishing

1 Introduction
Magnetic field-assisted finishing includes nontraditional and finishing techniques that enhance both surface quality and integrity of machined components. Among such techniques, magnetic abrasive finishing (MAF) can play a major role in micro-/nano-finishing, since it uses a magnetic field to force magnetic abrasive particles and abrasives onto a workpiece [1, 2], improving the quality of the polished surface. The earliest patent known regarding magnetic field-assisted finishing was granted in the USA in 1929 for the polishing of wire draw dies [3]. Since then, new approaches have been developed in both academia and industry to enhance the capabilities of the process. An example is the Magnetorheological Finishing (MRF) process, developed by Kordonski and his research group in the late 1980s [4]. Optical components are polished and material is removed in the presence of magnetic field and by the action of both magnetorheological (MR) fluid (microscale carbonyl iron particles dispersed in media) and abrasive particles [5]. The use of magnetorheological fluid for material removal in MRF processes is the main difference between them and MAF processes. Figure 1 shows the processing principle of both MAF and MRF processes. Figure 1 (a) shows a schematic of internal finishing of capillary tubes with MAF, being the magnetic field (created by the magnets) responsible for formation of flexible brush (abrasives and magnetic particles) and generation of polishing forces [6]. Figure 1 (b) shows a schematic of a vertical wheel-based machine, in which the magnetically stiffened MR fluid ribbon, delivered by a nozzle on the surface of a wheel, generates a pressure distribution in the gap. A shear flow of MR fluid and abrasive particles promotes material removal from the workpiece surface [5]. Flat, cylindrical, and complex geometries, made of different materials (including metals, ceramics, polymers, and composites), can be finished, resulting in surfaces having roughness ranges from sub-nanometer- to micrometer-scale. The material removal and finishing rates of the processes depend on...
the equipment/machine, process parameters, material, and geometry of the workpiece [7].

Magnetic field-assisted finishing can smooth surfaces [8, 9], deburr workpiece edges [10, 11], and alter surface hydrodynamic properties (e.g., wettability [12] and adhesion [13]), tribological properties (e.g., wear [14, 15] and friction [16]), and optical properties [17]. It has been successfully applied in aerospace [18, 19], electronics [20], textile [21], military [22], cosmetics [23], and the optics industry [24], improving product longevity and functionality.

The continuous advancements in the magnetic field-assisted finishing processes have led to a rapid increase in the number of relevant scientific publications over the past years. Bibliometric analysis is defined as a scientific method that involves mathematical and statistical operators to quantitatively examine a research field [25]. It has proven useful for indicating future directions and providing content investigations of research material published on several topics, including Additive Manufacturing (AM) [26], Industry 4.0 [27], Internet of Things [28, 29], sustainable manufacturing [30], lean manufacturing [31], COVID-19 [32], etc.

This study evaluated the scientific production and identified future direction(s) of magnetic field-assisted finishing through a bibliometric analysis. Descriptive and network mapping investigations were performed for the creation of scientific indicators based on the scientific publication growth and the most relevant papers, sources (journals, proceedings, conferences, etc.), countries, affiliations, authors, keywords, processes, and materials, and a comprehensive analysis of technological advances in magnetic field-assisted finishing revealed its challenges and future trends.

The remainder of the paper is structured as follows: Sect. 2 describes the adopted methodology; Sect. 3 reports the bibliometric results and the evolution of the processes/materials over time; Sect. 4 is devoted to analyses of the trends and their relationship with future opportunities; finally Sect. 5 provides the conclusions.

2 Methodology

The methodology was divided into two phases, namely data collection and data analysis.

2.1 Phase 1: Data collection

The scope and limitations of the data collection were determined by the search criteria (e.g., keywords, databases, time periods, and principles for document exclusion), and the combination of Boolean operators enabled the use of the following keywords to search titles, abstracts, and keywords (author, keyword, and keyword “plus”) of the published documents: (magnetorheological OR “magneto rheological” OR “magneto-rheological” AND (finishing OR “fluid finishing” OR “abrasive finishing”)) OR (“magnetic abrasive” AND finishing) OR “magnetic field assisted finishing” OR (“magnetic fluid” AND finishing) OR “magnetic barrel” OR “magnetic tumbling” OR “magnetic abrasive*” OR “magnetic compound fluid” OR “magnetic intelligent compound” OR “ferrofluidic finishing.” Words polishing, machining, and grinding were also used instead of finishing; symbol (*) means plural (or any character), and each term was placed between quotation marks (“””) for an exact search.

Web of Science and Scopus databases were the bases for researching the abovementioned keywords and capturing the broadest range of publications. No filters related to time span were applied so that all publications in the field until the end of 2021 could be analyzed. Only articles written in English were considered, and data preprocessing by R code and by a manual approach was required for the removal of duplicates. An interactive approach was adopted for the addition of more keywords in backward steps until the scope had been filled, thus enabling the start of the second step. In total, 1558 documents were selected in the survey for the bibliometric analysis and downloaded in a comma-separated-values (CSV) file format with all available information.
2.2 Phase 2: Data analysis

All data were analyzed using the Bibliometrix package, available for R (developed by Aria and Cuccurullo [33]). The choice of the software tool was supported by Muños et al. [34], who compared several tools available for bibliometric analyses, among which Bibliometrix provided the largest range of techniques tested. The analyses of productivity and citation of the papers, countries/affiliations (affiliations include centers, universities, institutes, companies, and others), sources (journals, proceedings, conferences, etc.), and authors were taken into account for the calculation of scientific indicators of magnetic field-assisted finishing.

The most cited sources were classified according to three scientific criteria, namely h-index (proposed by Hirsch [35]) and two variations; g-index (proposed by Egghe [36], which enabled measurements of global citation performance, and m-index (proposed by Molinari and Molinari [37]), which enabled comparisons of scientific careers from different times. The definition, applicability, advantages, and disadvantages of the indices are outside the scope of this research. The documents were classified according to (1) the process, (2) the class of the material, and (3) the purpose of the processes. Regarding the first category, the documents were divided in function of Magnetic Abrasive Finishing (MAF) and Magnetorheological Finishing (MRF) principles and their related processes (similar physical principles) and then subcategories were created. The materials belonging to the second category were classified into metal, ceramic, polymer, and composite. It must be highlighted that a single document may have analyzed different materials. Finally, seven items, namely “polishing,” “magnetic abrasive/MRF/Magnetic Compound Fluid (MCF) fabrication/characterization,” “deburring,” “edge finishing,” “cutting,” “surface texturing,” and “mechanical property alteration,” were defined for the third category. A factorial analysis based on the Multiple Correspondence Analysis (MCA) method and limited to 86 keywords plus was conducted for the map of keywords “plus” (Web of Science and Scopus databases refer to associated keywords as keywords “plus”).

3 Key findings on magnetic field-assisted finishing based on bibliometric analysis

3.1 Scientific production, citations, and sources of publication

Table 1 shows the distribution of types of the 1558 documents retrieved, of which most are composed of original articles (890; 57.1%), followed by conference papers (575; 36.9%).

| Document types | Results | [%] |
|---------------|---------|-----|
| Article       | 890     | 57.1|
| Conference paper | 575     | 36.9|
| Proceedings paper | 46      | 3.0 |
| Review        | 14      | 0.9 |
| Conference review | 12      | 0.8 |
| Book chapter  | 11      | 0.7 |
| Editorial     | 4       | 0.3 |
| Note          | 3       | 0.2 |
| Correction    | 1       | 0.1 |
| Report        | 1       | 0.1 |
| Short survey  | 1       | 0.1 |
| Total         | 1558    | 100 |

Figure 2 displays the number of publications per year from 1970 to 2021 (51 years). The first article on the list (indexed in the databases) was produced by Goloskov et al. [38], who improved the quality of external cylindrical surfaces by magnetic abrasives in hard-to-machine alloy steels. The average number of publications per year is 30.5, and the maximum number in one year was recorded in 2021 with 121 documents. Moreover, 344% of the documents were published in the past 5 years and 56.5% were published in the last 10 years. The 1558 documents resulted in 13320 citations on the date of data collection (02/10/2021), resulting in 8.5 average number of citations per document. During the survey time span, the average of citations per year showed a peak in 1990, due to the publication of the two most cited articles (i.e., [39] and [40]), which were the basis for the fundamental concepts for magnetic field-assisted finishing.

More studies on magnetic field-assisted finishing have addressed the demands of finishing component surfaces on the micro-/nano-scale. There has been an increased need for the finishing of complex geometry parts, driven by the extensive use of Additive Manufacturing (AM) in industry over recent years. The bibliometric analysis revealed twelve articles reported the development of post-processing finishing of additively manufactured materials by magnetic field-assisted finishing processes. In nine of them, the parts were built using the Selective Laser Melting (SLM) technique [41–49] and three applied Electron-Beam Melting (EBM) [50], Fused Deposition Modeling (FDM) [51], and Selective Laser Sintering (SLS) [52]. The use of MAF process for additively manufactured components may be a potential research area.

Table 2 shows the publications of highest number of global citations, of which the paper “Design and development of the magnetorheological abrasive flow finishing...
The MRAFF process,” published in 2004 by Prof. S. Jha and Prof. V. K. Jain [53], was cited most often: 211 times. According to Table 2, 9 out of 10 studies used an experimental approach, and most of them addressed the Magnetorheological Finishing (MRF) process due to a foundation for magnetic field-assisted finishing in the polishing of optical materials. The significant number of fundamental papers on MRF has led to an early growth in such technology and its more frequent implementation in the industry.

The 1558 papers were published in 353 sources (journals, proceedings, conferences, etc.) from 1970 to 2021. Table 3 shows the 10 sources with the greatest number of papers on the theme and their respective 2019 Impact Factors (IF). Since a foundation for those technologies was established for optics, the Proceedings of SPIE (The International Society for Optical Engineering) contained the greatest number of published papers: 192 (12.3% of the total).

Over the past 5 years, the International Journal of Advanced Manufacturing Technology (IJAMT) has showed the largest increase in the number of publications. Papers from 2018 to 2020 primarily dealt with the nanofinishing of flat surfaces, followed by cylindrical and complex (freeform) workpieces. Improvements in magnetic field-assisted finishing for parts with complex geometries (e.g., turbine blades), will impact the aerospace industry, benefitting the finishing of biomedical components such as knee replacements, which require nanoscale surface roughness and are, traditionally, manually polished.

Over the past 5 years, the International Journal of Advanced Manufacturing Technology (IJAMT) has showed the largest increase in the number of publications. Papers from 2018 to 2020 primarily dealt with the nanofinishing of flat surfaces, followed by cylindrical and complex (freeform) workpieces. Improvements in magnetic field-assisted finishing for parts with complex geometries (e.g., turbine blades), will impact the aerospace industry, benefitting the finishing of biomedical components such as knee replacements, which require nanoscale surface roughness and are, traditionally, manually polished.

Table 4 shows the top 10 most relevant sources in terms of total number of citations (TC) and number of documents (ND), as well as the h/g/m-indexes and the publication year of the first document analyzed here (referred to as PY-start). The Proceedings of SPIE (The International Society for Optical Engineering) had 2016 citations of 192 documents, thus being considered the most prolific and relevant source. The second was the International Journal of Machine Tools and Manufacture, with 1297 citations of only 26 documents. It can be concluded that papers on “magnetic field-assisted finishing” are cited in journals that cover the major fields of Production Engineering and in those related to Materials Science.

3.2 Geography of publications

Regarding the country of origin of the publications, Table 5 shows the 10 sources with the most productive/cited countries on the theme. Thirty-four countries were identified—20 in Europe, 11 in Asia (Russia and Turkey are transcontinental countries and were included in both Europe and Asia), 2 in North America, 2 in Africa, and 1 in Australia/Oceania. Researchers in China contributed with 424 documents, followed by India and the USA, and those from Asian countries accumulated the highest number of publications, as a result of the historical importance of the theme in their laboratories and industry. The USA has a significant number of publications due to their high production of items especially related to optics and with complex free-form surfaces.

More than 500 affiliations (centers, universities, institutes, companies, and others) were identified. Table 6 shows the top 10 sources with the greatest number of publications on magnetic field-assisted finishing. Among the universities, the University of Rochester (New York, USA) leads with 130 documents on the MRF process as the main research topic. QED Technologies (with locations in USA, Japan, France, China, and Korea) appear as the first company, with 93 documents, and the third institution overall. According to Harris [4], QED was founded in 1996 with 5 employees (Golini, Kordonski, Hogan, Dumas, and Edwards, who attended the University of Rochester and had expertise in MRF) in order to explore the commercial potential of MRF. Since then, MRF has been more frequently used in the industry and resources have been required for its expansion and improvements in the manufacture of parts through effective predictive algorithms and real-time adjustments in the process.
3.3 Authorship

Information-technology tools and algorithms have enabled data collection and bibliometric analyses in a structured way such as correlations among the works of several researchers in the field of interest. The identification of the main researchers and their countries and affiliations can suggest collaborative scientific projects that can lead to innovation in

Table 2 Most (global) cited references—main publications

| Refs | Country | TC¹ (TCY²) | Process | Approach | Main contribution |
|------|---------|------------|---------|----------|------------------|
| [53] | India   | 211 (12.4) | MRAFF¹  | Experimental | Development of MRAFF process. A weaker magnetic field (≈0.1 T) results in plowing of the surface, which does not improve the surface roughness much. Higher magnetic field strength (≈0.5 T) effectively remove peaks of surface leaving only valleys for a lower roughness |
| [5]  | USA     | 210 (9.5)  | MRF     | Mostly theoretical, some experimental | Overview on the development of the MRF process. It applies the laboratory experiments of [95] to an actual shop floor in industry. It shows the real-world advances of MRF in polishing and decreasing sub-surface damage on optical components |
| [96] | USA     | 148 (7.4)  | MRF     | Experimental | The addition of DI water to the MR fluid significantly increases the MRR of the MRF process on glass. Previously, the hardness of the CI (carbonyl iron) used was a major factor in the performance of MRF. Now, the addition of DI water makes the hardness a much less significant factor. Also, the importance of the size, type, and hardness of the nonmagnetic abrasive used in MRF on the MR was introduced |
| [97] | China   | 133 (10.2) | MRF     | Mostly experimental, some theoretical | MRF was used to (accurately and nondestructively) measure sub-surface damage caused by grinding and lapping of optical glass. A model was developed that establishes the relationship between sub-surface damage and surface roughness |
| [39] | Japan   | 130 (4.2)  | MAF     | Experimental | Fundamental equations for MAF, which defines the polishing force as a function of the volume of the magnetic particle, susceptibility of the particle, magnetic field strength, and its gradient. Equations showed that smaller diameter grains reduce MR rate, but can achieve lower surface roughness |
| [40] | Japan   | 128 (4.1)  | MFG⁴    | Theoretical | The viability of the typical MRF process combined with the use of ceramic balls that grind a rotating silicon nitride blank. There is success in grinding the diameter of the blank while also polishing the face of the blank |
| [98] | USA     | 125 (7.8)  | MRF     | Experimental | Foundation of the work of [97]. It uses MRF to determine sub-surface damage caused by grinding of optical materials. It is much quicker and nondestructive when compared to other methods of sub-surface measurement at the time |
| [70] | Taiwan  | 113 (5.9)  | MAF     | Experimental | Concluded that steel grit is more suitable for the MAF process than iron particles. Steel grit has superior hardness so a greater material removal can be achieved. Smaller magnetic abrasive (SiC) must be used to obtain a smaller surface roughness |
| [95] | USA     | 110 (4.2)  | MRF     | Experimental | Showed the ability of MRF to effectively polish and decrease the sub-surface damage of ground glass optical surfaces using a CNC machining center |
| [56] | India   | 109 (9.1)  | AFF, MAF, MRF, MRAFF, EEM, and MFP⁵ | Mostly theoretical, some experimental | Reviewed micro/nano machining processes |

¹Total Citations
²TC per Year
³Magnetorheological abrasive flow finishing
⁴Magnetic fluid grinding (another form of MRF)
⁵Abrasive Flow Finishing (AFF), Magnetic Abrasive Finishing (MAF), Magnetorheological Finishing (MRF), Magnetorheological Abrasive Flow Finishing (MRAFF), Elastic Emission Machining (EEM), and Magnetic Float Polishing (MFP)
academia and industry. Regarding the publication authorship analysis, 1950 different authors were identified in the 1558 documents, of which 58 (3.0%) were single-author ones. In total, 1088 authors (55.7%) produced only one document (one-timer authors) and 285 (14.6%) wrote two. Regarding authors’ collaboration, 84 documents (5.8%) were published by only one author (58 authors published 84 documents without co-authors).

Table 3 Top 10-most prolific sources

| Sources                                                      | ND  | [%] | 2019 IF |
|--------------------------------------------------------------|-----|-----|---------|
| Proceedings of SPIE—The International Society for Optical Engineering | 192 | 12.4| –       |
| Key Engineering Materials                                    | 93  | 6.0 | 0.22*   |
| International Journal of Advanced Manufacturing Technology   | 87  | 5.6 | 3.05    |
| Advanced Materials Research                                  | 65  | 4.2 | –       |
| Applied Optics                                               | 60  | 3.9 | 1.96    |
| Materials and Manufacturing Processes                        | 52  | 3.3 | 3.05    |
| Materials Science Forum                                      | 30  | 1.9 | 0.40    |
| International Journal of Machine Tools and Manufacture       | 30  | 1.9 | 8.02    |
| Precision Engineering                                        | 28  | 1.8 | 3.11    |
| Journal of Magnetism and Magnetic Materials                  | 24  | 1.5 | 2.72    |

*2005

Table 4 Top 10-most relevant sources

| #   | Source                                                        | TC | ND | h-index | g-index | m-index | PY-start |
|-----|--------------------------------------------------------------|----|----|---------|---------|---------|-----------|
| 1   | Proceedings of SPIE (The International Society for Optical Engineering) | 2016 | 192 | 23      | 39      | 0.9      | 1994      |
| 2   | International Journal of Machine Tools and Manufacture       | 1297 | 26 | 19      | 24      | 1.0      | 2002      |
| 3   | Applied Optics                                               | 1091 | 60 | 18      | 32      | 0.9      | 2000      |
| 4   | International Journal of Advanced Manufacturing Technology   | 1083 | 87 | 19      | 30      | 1.1      | 2003      |
| 5   | Journal of Materials Processing Technology                   | 724  | 20 | 13      | 17      | 0.5      | 1997      |
| 6   | Wear                                                         | 667  | 18 | 11      | 16      | 0.4      | 1990      |
| 7   | Materials and Manufacturing Processes                        | 645  | 52 | 17      | 24      | 1.1      | 2005      |
| 8   | CIRP Annals - Manufacturing Technology                       | 522  | 13 | 11      | 13      | 0.4      | 1990      |
| 9   | Precision Engineering                                        | 429  | 28 | 11      | 20      | 0.3      | 1984      |
| 10  | Journal of Intelligent Material Systems and Structures       | 264  | 13 | 7       | 9       | 0.3      | 1996      |

Table 5 Top 10-most productive/cited countries (based on country production)

| #   | Most productive Country | ND | Most cited Country | TC | Avg. article citations |
|-----|-------------------------|----|--------------------|----|-----------------------|
| 1   | China                   | 424| USA                | 4158| 15.4                  |
| 2   | India                   | 336| India              | 2859| 9.1                   |
| 3   | USA                     | 271| Japan              | 1628| 6.9                   |
| 4   | Japan                   | 236| China              | 1172| 2.8                   |
| 5   | South Korea             | 83 | South Korea        | 734 | 9.2                   |
| 6   | Iran                    | 37 | Taiwan             | 440 | 15.7                  |
| 7   | UK                      | 32 | Germany            | 322 | 11.5                  |
| 8   | Germany                 | 29 | Iran               | 131 | 3.6                   |
| 9   | Taiwan                  | 28 | UK                 | 109 | 3.4                   |
| 10  | Singapore               | 22 | Singapore          | 99  | 4.3                   |

Table 6 Top 10-most prolific affiliations

| Affiliations                                      | Countries | ND |
|--------------------------------------------------|-----------|----|
| University of Rochester                          | USA       | 130|
| Utsunomiya University                            | Japan     | 115|
| QED Technologies                                 | USA, Japan, France, China And Korea            | 93  |
| National University of Defense Technology         | China     | 70 |
| Indian Institute of Technology                   | India     | 66 |
| University of Florida                            | USA       | 54 |
| Akita Prefectural University                     | Japan     | 50 |
| Fukushima University                             | Japan     | 46 |
| Taiyuan University of Technology                 | China     | 39 |
| Indian Institute of Technology Delhi             | India     | 35 |


frequency was obtained by dividing the number of documents published by a given author by the number of co-authors, highlighting the individual author’s contribution. The top two researchers, in terms of published articles and articles fractionalized, addressed MAF and related processes as their main topics of interest.

3.4 Keyword conceptual boundaries

The authors’ keywords and keywords associated by Web of Science and Scopus databases (keywords “plus”) were analyzed regarding possible research directions and similarities among the themes addressed by the survey. The top 10 most frequent words are listed in Table 8. According to the results, the publications focused mostly on the roughness of the workpiece surface, indicating surface quality is an important output of the process and also directly related to mechanical, optical, and tribological properties (e.g., fatigue life, light reflectivity, and wear, respectively). Although material removal is not mentioned as frequently as surface roughness, it is often a secondary parameter tracked for helping control magnetic abrasive processes. Magnetic field-assisted finishing has also been used to obtain specific surface characteristics for wettability applications, showing its potential future path; however, those keywords do not appear in the search. Figure 3 displays trend topic keywords “plus” and the way they have changed over the years—the threshold number of words per year included was set to 1. According to Figure 3, several important words emerged from the analysis, and the most common in 2018 and 2019 was titanium alloys and aluminum alloys, respectively. The study of such materials may be a potential research area.

Figure 4 illustrates the conceptual structure of keywords “plus.” The data were organized into three primary clusters, in which the conceptual boundaries of magnetic field-assisted finishing are represented, and the plane distance shows the similarity between keywords “plus.” The closer to the center, the more frequent the use of the word as a keyword, highlighting the most studied themes. The first cluster (blue) contains 34 keywords related to the optical field (e.g., silicon, mirrors, and fabrication). The second cluster (green; 31 keywords) is associated with process parameters (input and output). It also includes abrasive particles, permanent magnets, and surface roughness, and some keywords are related to metrology, Nondestructive Testing (NDT), and ex situ techniques that can be used for surface inspection (e.g., atomic force microscopy (AFM) and scanning electron

Table 7 Authors with higher number of publications

| Authors            | Articles | Authors frac. | Articles frac. |
|--------------------|----------|---------------|----------------|
| Yamaguchi H¹       | 77       | Shinmura T²   | 29.5           |
| Shinmura T²        | 71       | Jain V³       | 23.6           |
| Jain V³            | 61       | Yamaguchi H¹  | 22.5           |
| Jacobs S⁴          | 59       | Singh A⁶      | 18.3           |
| Zhang Y⁵           | 50       | Jacobs S⁴     | 16.1           |
| Singh A⁶           | 46       | Jha S³        | 14.8           |
| Wang Y⁷            | 48       | Pandey P⁸     | 14.4           |
| Wu Y⁷              | 42       | Umehara N⁹    | 13.2           |
| Jha S³             | 41       | Kordonski W¹⁰ | 12.3           |
| Pandey P⁸          | 41       | Wang Y⁷       | 10.4           |

¹University of Florida (USA), ²Utsunomiya University (Japan), ³Indian Institute of Technology Kanpur (India), ⁴University of Rochester (USA), ⁵Institute of Mechanical Manufacturing Technology (China), ⁶Thapar Institute of Engineering and Technology (India), ⁷Akita Prefectural University (Japan), ⁸Indian Institute of Technology Delhi (India), ⁹Nagoya University (Japan), ¹⁰QED Technologies (Japan)

Table 8 Top 10-most frequent keywords (used by the authors and associated by the databases)

| Words (author)          | Occurrence | Words (plus)                      | Occurrence |
|-------------------------|------------|-----------------------------------|------------|
| Surface roughness       | 307        | Surface roughness                 | 529        |
| Magnetorheological      | 288        | Abrasive*                         | 501        |
| finishing (MRF)         | 198        | Magnetorheological finishing (and/or MRF) | 470       |
| Magnetic abrasive       | 127        | Polishing                         | 462        |
| finishing (MAF)         | 82         | Finishing                         | 301        |
| Magnetic abrasive       | 66         | Magnetic abrasive finishing (and/or MAF) | 297       |
| Magnetic field          | 65         | Magnetism                         | 259        |
| Material removal        | 55         | Magnetorheological fluids         | 255        |
| Magnetorheological fluid| 52         | Magnetic fields                   | 232        |
| Magnetorheological fluid| 52         | Magnetic abrasive*                | 140        |

* = wildcard including the plural
microscopy (SEM). Finally, the third cluster (red; 21 keywords) is composed of words related to concepts such as optimization, mathematical models, surface treatment, and deburring. Research on metrology techniques, analysis, and prediction of surfaces (internal and external) in real time (in situ techniques) may be a potential area of expansion for magnetic field-assisted finishing processes. Such techniques can also be combined with a system for in-process monitoring and controlling (e.g., closed-loop control), thus reducing the processing time and avoiding unnecessary stops for ex situ analyses of the surface.

3.5 Distinct characteristics among magnetic field-assisted finishing

Figure 5 displays the way the number of MAF- and MRF-related documents has changed over time. Table 9 shows the categorization of the documents according to the process (similar physical principles). MRF (509 documents on the process and 841 including other variations) was studied more than MAF (444 documents on the process and 670 including other variations). MAF shows a greater number of process variations than MRF, which can be justified by the need to meet specific project requirements and overcome the limitations of traditional magnetic field-assisted finishing processes, such as low material removal rate and high polishing time. Thus, the physical–chemical interactions between abrasive and part and advantages/limitations of the processes are fundamental factors that the researcher must know to obtain a satisfactory process in terms of material removal and finishing rate. Those factors define which magnetic field-assisted finishing process can be used, depending on the desired characteristics (e.g., roughness at nanometric levels) and need for the component to be manufactured/polished. Regarding physical characteristics among magnetic field-assisted finishing, in MRF, the magnetorheological fluid is continuously circulated and typically moves across the workpiece in conjunction with an electromagnet, improving the surface quality and integrity of the polished surface—with roughness range between 10 and 100 nm $R_t$ and 0.8 nm $R_q$ [54]. Since an electromagnet is the magnetic field generator in MRF, the strength of the magnetic field can be adjusted by changing the exciting current throughout the polishing process. Most works on MAF employ permanent magnets (as opposed to electromagnets); however, the magnetic field can be induced by two other ways: direct current and alternating current [55]. In MAF, two magnetic abrasive particles (MAPs) configurations can be used to polish the surface: bonded and/or unbonded. The first option produces better surface quality, and the second removes higher material removal rate [1]. Regarding the former, MAPs joined magnetically due to dipole–dipole interaction, form a flexible magnetic abrasive brush (FMAB), having loose abrasive phases with multiple cutting edges that act like a multi-point cutting tool for surface improvement [56]. Regarding the latter, the MAPs are mixed with a binder (having fixed abrasive phases); then, the tool is pressed and sintered for its use (resembling a grinding wheel used in grinding).
it is possible to build hybrid tools, which have both fixed and loose-abrasive phases [57, 58]. In MAF, through relative movements and the magnetic forces involved between MAPs (regardless of their configuration), magnetic poles, and the part, material is removed from the part (polishing) [7]. Thus, the geometric characteristics of the component are changed (roughness values decrease—possibly reaching the nanometer range, such as 0.003–0.07 μm $R_a$, and 0.03–0.7 μm $R_t$, $R_z$, $S_z$ [59])—and burrs are removed), improving the quality and integrity of the polished surface.

Table 10 shows most research on magnetic field-assisted finishing has been related to polishing. As stated in Sect. 3.1, IJAMT has shown the highest growth rate in recent years regarding magnetic field-assisted finishing. The papers offer an insight into the future trends of the technology. From 2018 to 2020, the topics of the publications in that journal changed from deburring and edge finishing to polishing, and their primary focus was on achieving nanoscale surface roughness on flat, cylindrical, and freeform surfaces.

### 3.6 Materials machined by magnetic field-assisted finishing

Figure 6 shows how the class of materials machined by magnetic field-assisted finishing processes has changed over the years. Among the 1558 papers, 763 reported the use of metallic components, and metal was the main class of materials for magnetic field-assisted finishing. In total, 548 studies involved ceramics, representing the second most studied class of materials, and only 21 and 7 studies analyzed polymers and composites, respectively. Hardness was the main reason why more metals and ceramics were polished as opposed to polymers and composites. The hardness of polymers and composites can substantially vary; however, the polymers commonly used are much softer than most of the metals and ceramics employed. The difficulty in polishing soft materials using abrasive processes is caused by abrasives plowing the surface and easily becoming stuck on it.
Table 9  Number of documents by each process

| MAF and related processes                  | ND  | MRF and related processes                  | ND  |
|-------------------------------------------|-----|-------------------------------------------|-----|
| MAF, MFAF or MAAF                        | 444 | MRF                                      | 509 |
| UMAAF, VAMAP, UEMAF or CUMAF             | 77  | MCFPP or C-MCFPP                          | 69  |
| EMAF                                      | 28  | MFG                                      | 52  |
| AMFAF                                     | 23  | MRAFF or R-MRAFF                          | 45  |
| MAD                                       | 17  | BEMRF                                    | 39  |
| MFF                                       | 17  | MRFF                                     | 18  |
| MFGA                                      | 9   | MRH, R-MRH or MRAH                       | 16  |
| DDMFA                                     | 8   | Clu-MRF, Clu-MRPP or Clu-MRCMP           | 15  |
| MAT                                       | 7   | CMMRF or CMRF                            | 15  |
| MIWS or MIFAWS                            | 7   | MRJF                                     | 14  |
| CMAF                                      | 6   | UV-MCFPP                                 | 15  |
| PMAF                                      | 5   | MRGPF or MRBGF                           | 7   |
| UADDMAF, CDDMAF or CUA-DDMAF              | 5   | MFP                                      | 6   |
| VMAF                                      | 4   | DMRF                                     | 5   |
| UHSMAF                                    | 3   | Lap-MRF                                  | 4   |
| MAH                                       | 2   | MCFR                                     | 3   |
| MAAFM                                     | 2   | Belt-MRF                                 | 3   |
| FMAG                                      | 1   | CDDMRF                                   | 3   |
| PM-2DVMAF                                 | 1   | MRBF                                     | 1   |
| WMAF                                      | 1   | UMRCF                                    | 1   |
| MABB                                      | 1   | NVMRF                                    | 1   |
| MGP                                       | 1   |                                          |     |
| MPP                                       | 1   | Total                                    | 841 |
| Total                                     | 670 |                                          |     |

Magnetic abrasive finishing (MAF), magnetic field-assisted finishing (MFAF), magnetically assisted abrasive finishing (MAAF), ultrasonic-assisted magnetic abrasive finishing (UAMAF), vibration-assisted magnetic abrasive polishing (VAMAP), ultrasonic-assisted electrochemical magnetic abrasive finishing (UEMAF), chemo-ultrasonic-assisted magnetic abrasive finishing (CUMAF), electrolytic (or electrochemical) magnetic abrasive finishing (EMAF), magnetic abrasive finishing by using alternating magnetic field (AMFAF), magnetic abrasive deburring (MAD), magneto abrasive flow finishing (MAFF), magnetic finishing with gel abrasive (MFGA), double-disk magnetic abrasive finishing (DDMAF), magnetic abrasive treatment (MAT), magnetic induction-free abrasive wire sawing (MIWS), magnetic induction-wire sawing (MIFAWS), chemo-assisted magnetic abrasive finishing (CMAF), fluid magnetic abrasive finishing (FMAF), ultrasonic-assisted double-disk magnetic abrasive finishing (UADDMAF), chemically assisted double-disk magnetic abrasive finishing (CDDMAF), chemo-ultrasonic-assisted double-disk magnetic abrasive finishing (CUA-DDMAF), viscoelastic magnetic abrasive finishing (VMAF), ultra-high-speed magnetic abrasive machining (UHSMAF), magnetic-assisted abrasive honing (MAH), magnetically assisted abrasive flow machining (MAAFM), flexible magnetic abrasive grinding (FMAG), planetary motion with two-dimensional vibration-assisted magnetic abrasive finishing (PM-2DVMAF), wire magnetic abrasive finishing (WMAF), magnetic-assisted ball burnishing (MABB), magnetic gasbag polishing (MGP), and magnetic pin polishing (MPP). MRF and related processes: magnetorheological finishing (MRF), Magnetic Compound Fluid Polishing Process (MCFPP), Chemical Magnetic Compound Fluid Polishing Process (C-MCFPP), Magnetic Fluid Grinding (MFG), magnetorheological abrasive flow finishing (MRAFF), rotational magneto rheological abrasive flow finishing (R-MRAFF), ball end magnetorheological finishing (BEMRF), magnetorheological fluid-based finishing (MRF), magnetorheological honing (MRH), rotational magnetorheological honing (R-MRH), magnetorheological abrasive honing (MRAH), clustered magnetorheological finishing (Clu-MRF), cluster magnetorheological-porous foam polishing (Clu-MRPP), cluster magnetorheological-chemical mechanical polishing (Clu-MRCMP), chemo-mechanical magnetorheological finishing (CMRMR), chemical magnetorheological finishing (CMRF), magnetorheological jet finishing (MRF), ultrasonic-vibration assisted magnetic compound fluid polishing process (UV-MCFPP), magnetorheological gear profile finishing (MRGPFF), magnetorheological bevel gear finishing (MRBGGF), magnetic float polishing (MFP), dual-rotation magnetorheological finishing (DRMRF), large polishing wheel—magnetorheological finishing (Lap-MRF), magnetic compound fluid finishing rubber (MCRF), belt magnetorheological finishing (Belt-MRF), chemical-assisted double-disc magnetorheological finishing (CDDMRF), magnetorheological brush finishing (MRBF), ultrasonic-magnetorheological combined finishing (UMRCF), and nonresonant vibration-assisted magnetorheological finishing (NVIMRF).
AISI 304 stainless steel is the material most polished by magnetic field-assisted finishing, tested in 153 studies. Austenitic stainless steels have high corrosion resistance and ductility (responsible for good drawing and forming properties) and are typically nonferromagnetic [60], and their applicability has been demonstrated in medical, nuclear [61], automotive, chemical, food processing [62], and other industries. However, they are considered to be difficult-to-machine materials. The next most studied materials are aluminum alloys (e.g., 6061, 5052, 2024, and others: 110 studies), single-crystal silicon (78 studies), fused silica (77 studies), and BK7 glass (58 studies). The bibliometric tool enabled an analysis of the origin of the processes assisted by magnetic fields and their historical development to date. Next Sect. 4 addresses the future trends of both academia and industry on the effective use of magnetic field-assisted finishing. The analysis is expected to help researchers and practitioners in MAF/MRF-related fields.

4 Trends for future research on magnetic field-assisted finishing

4.1 Application of MAF as post-additively manufacturing

As stated in Sect. 3.1, application of the MAF process for additively manufactured parts can be a potential research area. However, additively manufactured parts have a wide variety of initial surface state (e.g., microstructure, hardness, roughness, surface defects, porosity), which directly influence the finishing characteristics, including material removal rate (MRR), resulting surface roughness, and processing time. These effects on the finishing characteristics and mechanisms must be thoroughly studied. Table 11 shows studies on post-processing using MAF on parts made with AM, highlighting the impact of the initial surface roughness ($R_{ao}$, $R_n$) on the processing time. The surface roughness improvement ($\Delta R$) ranged from 77.9 to 99.9%, showing the ability of the process to reach smooth values, which, in some cases, are extremely difficult to achieve using traditional machining processes. Although the roughness reductions are high (up to 99.9%), a long processing time was required for such reduction (up to 4 h). Surface finishing is not only for improving surface roughness of a part. It enables meeting part specifications by altering surface conditions (including geometry (e.g., roughness and texture)), mechanical

### Table 11 Studies on MAF post-processing of parts made using AM

| Refs | Roughness ($\mu m$) | Processing time [min] |
|------|--------------------|-----------------------|
|      | $R_{ao}^1$         | $R_n^2$               | $\Delta R [%]^{3}$ |
|      | ($R_{ao}$)         | ($R_n$)               |                      |
| [45]* | 102.10             | 0.13                  | 99.87               | 240                   |
| [41] and [42] | 7.22              | 0.23                  | 96.81               | 180                   |
| [46]** | 12.05 (67.76)     | 2.68 (21.79)          | 77.76               | 75                    |
| [47]** | 12.44 (72)        | 2.85 (20)             | 77.09               | 75                    |
| [52]  | 16.00              | 0.89                  | 94.44               | 60                    |
| [44]* | $\approx 23 (80)$ | $\approx 3 (8)$      | 86.96               | 15                    |

*Experiment conditions 1. **Results of the vertically deposited sample ($0^\circ$).

1 Initial surface roughness

2 Final surface roughness

3 Surface roughness variation

### Table 10 Number of documents by purpose of process

| Purpose                      | Polishing | Magnetic abrasive/MRF/MCF fabrication/ characterization | Deburring | Edge finishing | Surface texturing | Cutting | Mechanical property alteration |
|------------------------------|-----------|----------------------------------------------------------|-----------|----------------|-------------------|---------|-------------------------------|
| ND                           | 1386      | 90                                                       | 25        | 17             | 9                 | 6       | 4                             |
properties (e.g., residual stress), chemical compositions, tribological performance, and so on. Finishing efficiency, such as material removal rate and time required to produce desired surface using MAF, is also important in practical applications. Moreover, materials and manufacturing methods evolve to match changing lifestyles, and surface-finishing technologies, such as MAF, must evolve together with the production changes. Accordingly, researchers are constantly advancing MAF.

For some additively manufactured parts, milling and grinding operations may be necessary prior to the magnetic field-assisted finishing for correcting geometric and dimensional errors, since the physical nature of the process (a motion-copying process) does not correct them. Moreover, including milling and grinding facilitates the MRR, shortening the processing time needed for MAF to achieve desired surface conditions. Motivated by the need to reduce the finishing time of parts made using AM, Teng et al. [43] used grinding as an intermediate post-processing step between SLM deposition and MAF. The initial surface roughness ($7 \mu m$ $R_z$) was reduced to approximately $0.6 \mu m$ $R_z$ after the grinding process, and MAF for 24 minutes resulted in a final surface roughness ($R_z$) of 0.16 $\mu m$. This resulted in a shorter polishing time in comparison with the use of only MAF after SLM deposition. Such a reduction shows the importance of designing process chains to achieve geometric and dimensional requirements and desired surface finish in shorter manufacturing time, thus, a more sustainable process chain for the parts produced by AM technologies.

The current technology enables the development of combined additive–subtractive machines, which improve the manufacturing process by combining deposition with machining and polishing in a single machine and gripping at only one position. This combined process does not require part un-chucking and re-chucking, which improves the part accuracy and saves time, space, and cost. The combined process has the potential to optimize the entire production route.

### 4.2 Hybrid magnetic field-assisted finishing

Zhu et al. [63] and Lauwers et al. [64] claimed processes undertaken simultaneously are considered hybrid, thus improving process efficiency. The combination of traditional MAF or MRF processes with other phenomena (e.g., electrochemical and ultrasonic ones) is another possible solution to improve MRR and potentially enhance finishing performance toward meeting industrial needs. The literature reports several hybrid applications with promising results [65–69]. Hybridization can help achieve the desired efficiency, but individual and interactive knowledge of the processes is one of the key elements. Despite the greater complexity involved during the process, the interrelationships between input and output parameters, as well as their effects on finishing results, must be well defined and known for a further development of hybridization. Therefore, the implementation of a hybrid machine/process for practical uses requires a deep and holistic analysis, including the boundaries of each process and the interrelationships between input and output parameters such as microstructure, residual stress, hardness, surface finish, form accuracy, and others, which minimize limitations and maximize advantages.

### 4.3 High-speed finishing

The usual tool rotation in MAF is lower than 1000 rpm, which corresponds to surface speeds lower than 65 m/min [39, 41, 44, 45, 52, 55, 70, 71]. On the other hand, high-speed machines have been developed and successfully used for increasing the material removal and decreasing polishing time. Kang et al. [72] conducted experiments using 30000 rpm (120 m/min circumferential speed of workpiece); the initial surface roughness (2–3 $\mu m$ $R_z$) was reduced in 10 min to 0.1 $\mu m$ $R_z$. Wang et al. [73] used 80,000 rpm (754 m/min circumferential speed of workpiece), improving the 0.21 $\mu m$ $R_z$ to 0.04 $\mu m$ in 75 seconds. Yin et al. [61] reported a 0.32 $\mu m$ to 0.03 $\mu m$ ($R_z$) surface roughness improvement in only 40 seconds of polishing time at 80000 rpm (120 m/min).

### 4.4 Magnetic tool behavior

The development of new and more efficient auxiliary tools (e.g., magnetic abrasives, abrasive particles, and fluid) can shorten processing time, increase MRR, and provide even lower tolerances for machined components. Other possible solutions include new magnetic field configurations, such as multi-magnetic poles [74–76], new methods [77–79] or new tool configurations [80–88], and improvements in magnetic tools (combination of aggressive polishing and then lower MRR as the process continues [89] or fixed/loose-abrasive configuration [57, 58]).

In general, the finished area is determined by the area of contact of magnetic tool (e.g., magnetic-particle brush) against the target surface, which corresponds to the size of the magnetic field generator (e.g., permanent magnet) or pole tip attached to the magnet to adjust the magnetic field at the finished area. Simple enlargement of the permanent magnet is neither effective nor practical. However, the magnetic-particle brush exhibits unique behavior—naturally conforms to the part geometry during finishing—that can be useful. Furthermore, the brush characteristics and behavior, such as stiffness and movement, can be controlled by altering the magnetic field, and the characteristic tool behavior makes MAF applicable to the finishing of complex surface of various roughness levels. Therefore, design of the magnetic field (including the use of multiple magnets and optimizing the pole-tip geometries) and the effects on magnetic-particle...
brush and abrasive behaviors can be additional key research areas.

4.5 Process modeling

Not all magnetic field-assisted finishing processes lead to effective modeling solutions. Process modeling is one of the limitations of MAF compared to MRF, which can be overcome with advancements in reliable simulations of the MAF process, leading to prediction and control of both surface roughness and MRR, as in MRF. Accurate magnetic field-assisted finishing models that take into account MRR and surface quality constraints are sought for. Many models for MAF and MRF recently reported have aimed to fill this gap and to better understand the way input parameters affect MRR and roughness [66, 76, 90–92].

Kala et al. [93] pointed out that modern industries seek manufacturing processes that can be automated. Therefore, models must be developed for the achievement of process control and automation of MAF in future industries. Aurich et al. [94] highlighted practical applications (at the industrial level) are hampered by the lack of models that can accurately predict MRR and the roughness of the parts. Process modeling will help the industrial implementation of the process. Table 12 shows a summary of the last publications with proposals of theoretical modeling of MAF, which lead to the conclusion that cutting forces and pressures are directly correlated to surface quality and MRR during the MAF process. However, mathematical models involve some simplifications in order to reduce their complexity. Each model has advantages and limitations, depending on the conditions and assumptions adopted. For instance, all publications involved analytical equations with experimental validation and considered the magnetic abrasive particles (MAPs) to be perfectly spherical particles. The studies assumed the surface roughness profile was triangular, and the physical and mechanical properties of MAPs remained constant during the process. Therefore, the interaction between parts and MAPs (effect of micro-cutting, extrusion, multiple elastic–plastic deformations, friction, corrosion, wear, finishing medium, and others) must be incorporated into future models for providing a more realistic output. A combination of the existing models, i.e., combined modeling, which contains the main contributions of each study in a single model, can also be a possible solution to overcome this challenge.

5 Conclusions

This paper has evaluated a bibliometric analysis of magnetic field-assisted finishing conducted over the past 51 years, identifying limitations, challenges, and means to overcome them and provide future direction(s). The major findings are listed below:

1. The retrieved records showed a rising trend in publications on magnetic field-assisted finishing. From 1970 to 2021, out of 1558 documents, 56% were published in the last 10 years.

2. Since the foundation of the magnetic field-assisted finishing process was established in the field of optical science, 22.2% of the papers were published in journals whose primary topic was optics. The number of publications on advanced manufacturing technologies, materials, and precision engineering in other journals showed an increase.

3. Most published documents were authored in Asia, led by institutes from China and India that conduct research on defense technology and ultraprecision. Researchers from USA were the third most productive and the most cited ones due to the strong connection between academia (University of Rochester) and industry (QED Technology).

4. Metals were the most studied class of materials, followed by ceramics. AISI 304 stainless steel was the most tested metal, due to high demands in several industries.

Table 12  Comparison of the MAF process models

| Refs | Model focus | Main contribution |
|------|-------------|-------------------|
| [93] | Roughness   | Consideration about physical aspects (abrasive with normal size distribution, frictional forces, FMAB* chains inclination) that affect roughness |
| [99] | Roughness   | Consideration about instantaneous surface roughness |
| [100]| MR          | Consideration of stationary and independent transient phenomena that affect material removal |
| [101]| MR          | Consideration of the effect of shear and plowing forces that affect the mechanisms of micro-cutting and wear pattern during the process |
| [102]| MR          | Consideration about mechanisms of contact and interaction between abrasive and magnetic particles on FMAB* |
| [47] | MR          | Consideration about effects of the initial surface roughness on the indentation depth |
| [103]| MR          | Consideration on elastic deformation and material recovery |

*Flexible magnetic abrasive brush (FMAB)
5. The application of magnetic field-assisted finishing as post-additive manufacturing process yielded promising results, thus leading to new applications and a potential research area. Further studies are needed to quantify the effects of initial state of parts made using AM (microstructure, hardness, roughness, surface defects, porosity, among others) on the overall process time and part surface quality.

6. Five potential research areas were identified for the future research trends that will lead magnetic field-assisted finishing to new applications and practical use: (a) application of magnetic field-assisted finishing as a post-additive-manufacturing process, (b) hybrid magnetic field-assisted finishing, (c) improvement of finishing efficiency by high-speed finishing, (d) clarification of magnetic-tool behavior, and (e) establishment of accurate process models. Biomedical, aerospace, and die-and-mold industries can be positively impacted by the technological advances in MAF/MRF processes. However, MAF/MRF should not be viewed as a competitor to other existing technologies but rather as a complementary process that aids in surface finishing of parts that cannot be processed in conventional ways.

Acknowledgements This work was supported by São Paulo Research Foundation (FAPESP) (Grant numbers 2016/11309-0 and 2019/10758-4) and National Council for Scientific and Technological Development (CNPq).

Author’s contribution Conceptualization, methodology, data curation, investigation, writing—original draft preparation were performed by SAM and RJ; supervision, writing—review and editing were performed by SEJ and YH. All authors have read and agreed to the published version of the manuscript.

Declarations

Conflict of interest The authors have no conflict of interest to declare.

References

1. Heng L, Kim Y-J, Mun S-D (2017) Review of superfinishing by the magnetic abrasive finishing process. High Speed Mach 3(1):42–55. https://doi.org/10.1515/hsm-2017-0004
2. Mohannad Naem H (2016) A comprehensive review on magnetic abrasive finishing process. Adv Eng Forum 18:1–20. https://doi.org/10.4028/www.scientific.net/AF.18.1
3. Simons A (1929) Method of polishing wire-drawing dies and apparatus therefor, US Patent 1,698,458
4. Harris DC (2011) History of magnetorheological finishing. Window Dome Technol Mater XII 8016:80160N. https://doi.org/10.1117/12.882557
5. Golini D, Kordonski WL, Dumas P, Hogan SJ (1999) Magnetorheological finishing (MRF) in commercial precision optics manufacturing. Opt Manuf Test III 3782(2July):80–91. https://doi.org/10.1117/12.369174
6. Yamaguchi H, Shimamura T, Ikeda R (2007) Study of internal finishing of austenitic stainless steel capillary tubes by magnetic abrasive finishing. J Manuf Sci Eng, Trans ASME 129(5):885–892. https://doi.org/10.1115/1.2738957
7. Yang S, Li W (2018) Surface finishing theory and new technology. National defense industry press and springer-verlag GmbH Germany, Beijing. 1 edition. https://doi.org/10.1007/978-3-662-54133-3
8. Shinmura T, Takazawa K, Hatano E (1986) Study on magnetic-abrasive finishing (1st report) -on process principle and a few finishing characteristics-. J Japan Soc Precision Eng 52(5):851–857. https://doi.org/10.2493/jjpece.52.851
9. Sidpara A, Jain VK (2012) Nano-level finishing of single crystal silicon blank using magnetorheological finishing process. Tribol Int 47:159–166. https://doi.org/10.1016/j.triboint.2011.10.008
10. Kodácsy J, Szabó A (2014) Burr formation in metal cutting operations and some deburring methods. Key Eng Mater 581:235–240. https://doi.org/10.4028/www.scientific.net/KEM.581.235
11. Ko SL, Park JI, Baron Y (2007) Micro deburring for precision parts using magnetic abrasive finishing method. J Mater Process Technol 187–188:19–25. https://doi.org/10.1016/j.jmatprot.2006.11.183
12. Graziano AA, Ganguly V, Schmitz T, Yamaguchi H (2014) Control of lay on cobalt chromium alloy finished surfaces using magnetic abrasive finishing and its effect on wettability. J Manuf Sci Eng, Trans ASME 136(3):1–8. https://doi.org/10.1115/1.4026935
13. Boggs T, Carroll R, Tran-Son-Tay R, Yamaguchi H, Al-Mousily F, DeGroff C (2014) Blood cell adhesion on a polymeric heart valve leaflet processed using magnetic abrasive finishing. J Med Devices 8(1):1–8. https://doi.org/10.1115/1.4025853
14. Kanish TC, Narayanan S, Kuppan P, Denis AS (2018) Investigations on wear behavior of magnetic field assisted abrasive finished SS316L material. Mater Today: Proc 5(5):12734–12743. https://doi.org/10.1016/j.matpr.2018.02.257
15. Kunal A, Anant Kumar S (2021) Magnetorheological finishing of polylamide materials for improving their functional performance. J Brazilian Soc Mech Sci Eng 43(12):1–23. https://doi.org/10.1007/s40430-021-03284-y
16. Li W, Zhou P, Lin W-C, Nteziyaremye V, Yamaguchi H, Guo D, Shih A (2016) Effects of needle inner surface topography on friction and biopsy length. Int J Mech Sci 119:412–418. https://doi.org/10.1016/j.ijmecsci.2016.11.005
17. Sharma A, Ranjan P, Datta B, Balasubramaniam R (2014) A comparative study on the reflectivity of metallic mirrors finished by deterministic and random processes. All India Manufacturing Technology, Design and Research Conference (AIMTDR), pages 201–206
18. Wang Y, Dejin H (2005) Study on the inner surface finishing of tubing by magnetic abrasive finishing. Int J Mach Tools Manuf 45(1):43–49. https://doi.org/10.1016/j.ijmachtods.2004.06.014
19. Sato T, Kum C-W, Venkatesh VC (2013) Rapid magneto-rheological finishing of Ti-6Al-4V for aerospace components. Int J Nanomanuf 9(5–6):431–445. https://doi.org/10.1504/IJNM.2013.057590
20. Kordonski W, Jacobs S (1996) Model of magnetorheological finishing. J Intell Mater Syst Struct 7(2):131–137. https://doi.org/10.1177/1045389X960070202
21. Manpreet S, Anant Kumar S (2020) Magnetorheological finishing of grooved drum surface and its performance analysis in winding process. Int J Adv Manuf Technol 100(7–8):2921–2937. https://doi.org/10.1007/s00170-019-04812-w
22. Kajal S, Jain VK, Ramkumar J, Nagdeva L (2017) Experimental and theoretical investigations into internal magnetic abrasive finishing of a revolver barrel. Int J Adv Manuf Technol 100(5–8):1105–1122. https://doi.org/10.1007/s00170-017-1220-2
56. Jain VK (2009) Magnetic field assisted abrasive based micro- nano-finishing. J Mater Process Technol 209(20):6022–6038. https://doi.org/10.1016/j.jmatprotec.2009.08.015

57. Yamaguchi H, Nteziyaremye V, Stein M, Li W (2015) Hybrid tool with both fixed-abrasive and loose-abrasive phases. CIRP Annals - Manuf Technol 64(1):337–340. https://doi.org/10.1016/j.cirp.2014.04.006

58. Zou Y, Satou R, Yamazaki O, Xie H (2021) Development of a new finishing process combining a fixed abrasive polishing with magnetic abrasive finishing process. Machines 9(4):1–14. https://doi.org/10.3390/machines9040081

59. Hashimoto F, Yamaguchi H, Krajnik P, Wegener K, Chaudhari R, Hoffmeister H-W, Kuster F (2016) Ablasive fine-finishing technology. CIRP Annals - Manuf Technol 65(2):597–620. https://doi.org/10.1016/j.cirp.2016.06.003

60. Matweb. Online materials information resource, 2021. matweb.com

61. Yin C, Wang R, Kim J-S, Lee S-W, Mun S-D (2019) Ultra-high-speed magnetic abrasive surface micro-machining of AISI 304 cylindrical bar. Metals 9(5):87. https://doi.org/10.3390/met9050048

62. Judal KB, Yadava V (2013) Cylindrical electrochemical magnetic abrasive machining of AISI-304 stainless steel. Mater Manuf Processes 28(4):449–456. https://doi.org/10.1080/10426914.2012.736653

63. Zhu Z, Dhokia VG, Nassehi A, Newman ST (2013) A review of hybrid manufacturing processes - state of the art and future perspectives. Int J Computer Integr Manuf 26(7):596–615. https://doi.org/10.1080/10426914.2013.836653

64. Lauwers B, Klocke F, Klink A, Erman Tekkaya A, Neugebauer R, McIntosh D (2014) Hybrid processes in manufacturing. CIRP Annals - Manuf Technol 63(2):561–583. https://doi.org/10.1016/j.cirp.2014.05.003

65. Pandey K, Pandey PM (2019) An integrated application of chemo-ultrasonic approach for improving surface finish of Si (100) using double disk magnetic abrasive finishing. Int J Adv Manuf Technol 103(9–12):3871–3886. https://doi.org/10.1007/s00170-019-03829-5

66. Liang H, Yan Q, Jiabin L, Luo B, Xiao X (2019) Material removal mechanisms in chemical-magnetorheological compound finishing. Int J Adv Manuf Technol 103(1–4):1337–1348. https://doi.org/10.1007/s00170-019-05394-5

67. Misra A, Pandey P-M, Dixit U-S, Roy A, Silberschmidt V-V (2018) Multi-objective optimization of ultrasonic-assisted magnetic abrasive finishing process. Int J Adv Manuf Technol 101(5–8):1661–1670. https://doi.org/10.1007/s00170-017-1459-7

68. Sun X, Zou Y (2018) Study on electrolytic magnetic abrasive finishing for finishing stainless steel SUS304 plane with a special compound machining tool. J Manuf Mater Process 2(3):41. https://doi.org/10.3390/jmmp2030041

69. Liang H, Jiabin L, Pan J, Yan Q (2017) Material removal process of single-crystal SiC in chemical-magnetorheological compound finishing. Int J Adv Manuf Technol 94(5–8):2939–2948. https://doi.org/10.1007/s00170-017-1098-z

70. Chang G-W, Yan B-H, Hsu R-T (2002) Study on cylindrical magnetic abrasive finishing using unbounded magnetic abrasives. Int J Mach Tools Manuf 42(5):575–583. https://doi.org/10.1016/S0890-6955(01)00153-5

71. Singh L, Kumar H, Kumar A (2017) Parametric study in surface finishing of inconel 718 surface with magnetic abrasive finishing process. Int J Mech Prod Eng Res Develop 7(4):223–234. https://doi.org/10.24247/impredaug1723

72. Kang J, George A, Yamaguchi H (2012) High-speed internal finishing of capillary tubes by magnetic abrasive finishing. Proc CIRP 1(1):414–418. https://doi.org/10.1016/j.procir.2012.04.074

73. Wang R, Lim P, Heng L, Kim M-S, Mun S-D (2016) Characteristics of ultra-high-speed micro processing machines using magnetic abrasive machining methods. J Mech Sci Technol 30(10):4687–4695. https://doi.org/10.1007/s12206-016-0939-2

74. Tian Y, Shi C, Fan Z, Zhou Q (2020) Experimental investigations on magnetic abrasive finishing of Ti-6Al-4V using a multiple pole-tip finishing tool. Int J Adv Manuf Technol 106(7–8):3071–3080. https://doi.org/10.1007/s00170-019-04871-z

75. Luo B, Yan Q, Pan J, Guo M (2020) Uniformity of cluster magnetorheological finishing with dynamic magnetic fields formed by multi-magnetic rotating poles based on the cluster principle. Int J Adv Manuf Technol 107(1–2):919–934. https://doi.org/10.1007/s00170-020-05088-1

76. Meng N, Jianguo C, Yueming L, Jianyong L (2018) Influence of magnets phyllotactic arrangement in cluster magnetorheological effect finishing process. Int J Adv Manuf Technol 99(5–8):1699–1712. https://doi.org/10.1007/s00170-018-2603-8

77. Cao J, Li J, Nie M, Zhu P, Zhao C, Zhang J, Xuan T, Jinhuang X, Li B (2019) A novel surface polishing method and its fundamental performance in ultra-fine polishing of wafer. Int J Adv Manuf Technol 105(7–8):2919–2933. https://doi.org/10.1007/s00170-019-04473-9

78. Talwinder SB, Anant Kumar S (2018) An initial new approach for magnetorheological finishing of ferromagnetic internal cylindrical surfaces. Int J Adv Manuf Technol 100(5–8):1017–1030. https://doi.org/10.1007/s00170-018-2031-9

79. Guan F, Hao H, Li S, Liu Z, Peng X, Shi F (2018) A novel Lap-MRF method for large aperture mirrors. Int J Adv Manuf Technol 95(9–12):4643–4657. https://doi.org/10.1007/s00170-017-1498-0

80. Jinzhong W, Yin S, Xing B, Zou Y (2019) Effect of magnetic pole on finishing characteristics in low-frequency alternating magnetic field for micro-groove surface. Int J Adv Manuf Technol 104(9–12):4745–4755. https://doi.org/10.1007/s00170-019-04362-1

81. Alam Z, Khan D-A, Jha S (2018) MR fluid-based novel finishing process for nonplanar copper mirrors. Int J Adv Manuf Technol 101(1–4):995–1006. https://doi.org/10.1007/s00170-018-2998-2

82. Sahil M, Anant Kumar S (2017) Nano-surface finishing of hardened AISI 52100 steel using magnetorheological solid core rotating tool. Int J Adv Manuf Technol 95(1–4):513–526. https://doi.org/10.1007/s00170-017-1209-x

83. Wang Y, Yin S, Tian H (2018) Ultra-precision finishing of optical mold by magnetorheological polishing using a cylindrical permanent magnet. Int J Adv Manuf Technol 97(9–12):3583–3594. https://doi.org/10.1007/s00170-018-2199-z

84. Barman A, Das M (2017) Toolpath generation and finishing of bio-titanium alloy using novel polishing tool in MFAF process. Int J Adv Manuf Technol 100(5–8):1123–1135. https://doi.org/10.1007/s00170-017-1050-2

85. Nagdev L, Jain VK, Ramkumar J (2017) Preliminary investigations into nano-finishing of freeform surface (femoral) using inverse replica fixture. Int J Adv Manuf Technol 100(5–8):1081–1092. https://doi.org/10.1007/s00170-017-1459-7

86. Vishwas G, Anant Kumar S (2017) Improved design of magnetorheological honing tool based on finite element analysis and experimental examination of its performance. Int J Adv Manuf Technol 100(5–8):1067–1080. https://doi.org/10.1007/s00170-017-1149-5

87. Dilshad AK, Sunil J (2017) Selection of optimum polishing fluid composition for ball end magnetorheological finishing (BEMRF) of copper. Int J Adv Manuf Technol 100(5–8):1093–1103. https://doi.org/10.1007/s00170-017-1056-9

88. Sirwal S-A, Singh A-K, Paswan S-K (2020) Experimental analysis of magnetorheological finishing of blind hole surfaces using...
permanent magnet designed tools. J Brazilian Soc Mech Sci Eng 42(3):1–23. https://doi.org/10.1007/s40430-020-2225-6
89. Stein M, Yamaguchi H (2017) Effect of binder content on hybrid magnetic tool behavior. Proceedings of the ASME 2017 12th International Manufacturing Science and Engineering Conference (MSEC2017)-2980, pages 1–6
90. Ghosh G, Dalabehera RK, Sidpara A (2018) Parametric study on influence function in magnetorheological finishing of single crystal silicon. Int J Adv Manuf Technol 100(5–8):1043–1054. https://doi.org/10.1007/s00170-018-2330-1
91. Pan J, Guo M, Yan Q, Zheng K, Xiao X (2018) Research on material removal model and processing parameters of cluster magnetorheological finishing with dynamic magnetic fields. Int J Adv Manuf Technol 100(9–12):2283–2297. https://doi.org/10.1007/s00170-018-2747-6
92. Jain V-K, Saren K-K, Raghuram V, Ravi Sankar M (2016) Force analysis of magnetic abrasive nano-finishing of magnetic and non-magnetic materials. Int J Adv Manuf Technol 100(5–8):1137–1147. https://doi.org/10.1007/s00170-016-8954-0
93. Kala P, Sharma V, Pandey PM (2017) Surface roughness modelling for double disk magnetic abrasive finishing process. J Manuf Processes 25:37–48. https://doi.org/10.1016/j.jmapro.2016.10.007
94. Aurich JC, Kirsch B, Setti D, Axinte D, Beaucamp A, Butler-Smith P, Yamaguchi H (2019) Abrasive processes for micro parts and structures. CIRP Annals - Manuf Technol 68(2):653–676. https://doi.org/10.1016/j.cirp.2019.05.006
95. Jacobs SD, Golini D, Hsu Y, Puchebner BE, Strafford D, Kordonski WJ, Prokhorov IV, Ess E, Pietrowski D, Kordonski VW (1995) Magnetorheological finishing: a deterministic process for optics manufacturing. Proc. SPIE, International Conference on Optical Fabrication and Testing, 2576:372–382. https://doi.org/10.1117/12.215617
96. Shorey AB, Jacobs SD, Kordonski WJ, Gans RF (2001) Experiments and observations regarding the mechanisms of glass removal in magnetorheological finishing. Appl Opt 40(1):20. https://doi.org/10.1364/ao.40.000020
97. Li S, Wang Z, Yulie W (2008) Relationship between subsurface damage and surface roughness of optical materials in grinding and lapping processes. J Mater Process Technol 205(1–3):34–41. https://doi.org/10.1016/j.jmatprotec.2007.11.118
98. Randi JA, Lambropoulos JC, Jacobs SD (2005) Subsurface damage in some single crystalline optical materials. Appl Opt 44(12):2241–2249. https://doi.org/10.1364/AO.44.002241
99. Aviral M, Pandey Pulak M, Dixit US (2017) Modeling and simulation of surface roughness in ultrasonic assisted magnetic abrasive finishing process. Int J Mech Sci 133:344–356. https://doi.org/10.1016/j.ijmecsci.2017.08.056
100. Misra A, Pandey Pulak M, Dixit US (2017) Modeling of material removal in ultrasonic assisted magnetic abrasive finishing process. Int J Mech Sci 131–132:853–867. https://doi.org/10.1016/j.ijmecsci.2017.07.023
101. Shukla Vipin C, Pandey Pulak M, Dixit Uday S, Roy A, Silberschmidt V (2017) Modeling of normal force and finishing torque considering shearing and ploughing effects in ultrasonic assisted magnetic abrasive finishing process with sintered magnetic abrasive powder. Wear 390–391:11–22. https://doi.org/10.1016/j.10.1016/j.wear.2017.06.017
102. Kum C-W, Sato T, Guo J, Liu K, Butler D (2018) A novel media properties-based material removal rate model for magnetic field-assisted finishing. Int J Mech Sci 141:189–197. https://doi.org/10.1016/j.ijmecsci.2018.04.006
103. Gao Y, Zhao Y, Zhang G, Yin F, Zhang H (2020) Modeling of material removal in magnetic abrasive finishing process with spherical magnetic abrasive powder. Int J Mech Sci. https://doi.org/10.1016/j.ijmecsci.2020.105601

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.