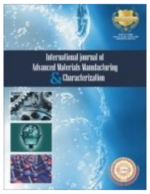

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Comprehensive Review Of Current Research Trends In Magnetic Abrasive Finishing (Maf) Process

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ABSTRACT

Magnetic Abrasive Finishing (MAF) process is a nontraditional machining process which has been developed to improve the surface quality and to remove burrs of the workpiece. The MAF can be maneuvered to finish 'difficult surfaces' like the internal surface of capillary tube, needle, and elbows. In MAF, a mixture of abrasives and ferromagnetic particles named as magnetic abrasives act as a multipoint cutting tool. The magnetic abrasives form a Magnetic Abrasive Flexible Brush (MAFB) due to the action of the magnetic field and provide the finishing of theworkpiece surface. This paper reviews the research trends by considering various aspects of MAF likeMagnetic abrasives, theHybrid approach in MAF, Applications of MAF for industrial products, Modeling & simulation in MAF, different types of abrasives, theshape of theworkpiece. The information collected from research studiesissummarized and presented in the form of graphs.

Keywords: MAF, abrasives, MAPs, Hybrid approach etc.

1. INTRODUCTION

In recent years, a special attention in manufacturing technology has been dedicated to finishing operations with an objective to narrow down the finishing tolerance of workpieces. This has led to the development of different types of innovative manufacturing techniques, and Magnetic Abrasive Finishing (MAF) process is one of these processes. A mixture of abrasives and ferromagnetic particles called as magnetic abrasives act as a multipoint cutting tool in this process. The magnetic abrasives, placed between the magnetic poles, form a Magnetic Abrasive Flexible Brush (MAFB) due to the action of the magnetic field. The MAFB rubs against the workpiece surface and provides the finishing action. Besides other machining parameters, cutting forces play an important role in developing the required surface texture of the workpiece.In MAF cutting forces are controlled by amagnetic field which in turn controlled by electric current supplied to the electromagnet. So, there is a precise control of cutting forces in MAF process. The MAF method offers a number of advantages over the conventional techniques of abrasive treatment [1, 2]: (i) magnetic abrasives adapt to the shape of workpiece surface hence allows finishing of complex-shaped components; (ii) due to flexible nature of MAFB it does not suffer from overloading; (iii) low cutting temperature (iv) cutting force is proportional to magnetic field strength which in turn depends upon the gap between the pole and the workpiece surface, less the gap more will be the magnetic field strength and hence more cutting force. As the gap at ridges of the surface is less so, surface ridges (magnetic field concentrators) are cut off selectively.

This paper reviews the research trends on various aspects of MAF, like Magnetic abrasives, the Hybrid approach in MAF, Applications of MAF for industrial products, different types of abrasives, the shape of the workpiece,Modeling & simulation in MAF. A detailed study has been carried out of research papers, results are summarizedand presented in the form of graphs.Although this method was introduced in 1938 in the Soviet Union, but in this review paper recent research studies, for the last 25 years, has been collected and presented.

2. MAGNETIC ABRASIVES

In MAF magnetic abrasives, acting as amultipoint cutting tool, are very critical in ensuring finishing of desired quality and accuracy. The different techniques of preparing magnetic abrasives are Coated type, Unbonded Magnetic Abrasives, Bonded Magnetic Abrasives, Gel adhesives and Plasma spray.

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2.1 Coated Magnetic Abrasives

Shinmura et al [1] studied MAF process for finishing of Si_3N_4 ceramic bars with coated magnetic abrasives. Coated magnetic abrasives were prepared by electrodepositing dispersedly diamond grains on the surface of cast iron balls. Tests indicated that surface roughness of workpiece is obtained as low as 0.04 µm(Ra) and precision edge finishingabout 0.01mm radius in 30min of machining time. It has also been observed that coated layer of abrasivesgetsworn out from the magnetic particle while in theprocess, thus disturbing the finishing performance.

2.2 Unbonded Magnetic Abrasives (UMA)

Unbonded Magnetic Abrasives (UMA) is a mechanical mixture of abrasive and ferromagnetic particles, in some suitable ratio, with a lubricant. This type of magnetic abrasives is also called as 'simply mixed magnetic abrasives'. While going through the literature survey it has been found that a lot of research studies on MAF have been carried outby using UMA. The research studies in this category are classified on the basis of'phases of development' in MAF, as shown in Fig 1. These phases are discussed in the following sections:

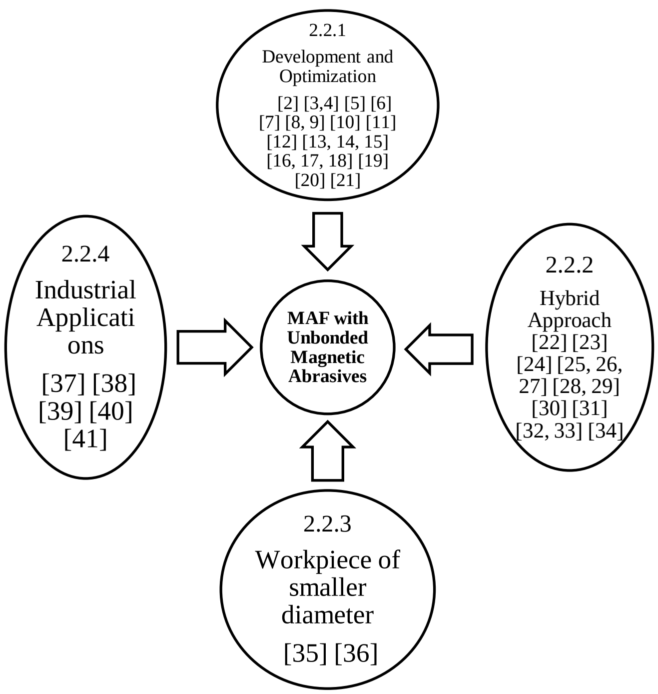

Fig 1: *MAF with Unbonded Magnetic Abrasives in the literature*

2.2.1 Development and optimization

Fox. et al [2] prepared Al_2O_3 based UMA for polishing of stainless steel rods and achieved surface roughness as low as 10nm. Yamaguchi et al [3, 4] studied the mechanism of material removal for finishing of Stainless Steel disc. It was established that magnetic field distribution has a predominant effect on the abrasive behavior in the finishing of theinner surface of stainless steel tube while using Al_2O_3 based UMA. Jain et al [5] found that surface roughness of theinner surface of stainless steel tube improves with anincrease in circumferential speed of workpiece by using Al_2O_3 based UMA. Chang et al [6] prepared SiC-based UMA by mixing with steel grits and iron grits for finishing of outside surface of SKD11 steel rods and found that Steel grit is more suitable than iron grit because of its superior hardness and the polyhedron shape. Yamaguchi et al [7] achieved surface roughness as fine as 0.02µm of alumina-based ceramic tubes by using diamond based UMA. Yin et al [8, 9] characterized effects of vibration of theworkpiece in finishing of brass plates by using Al_2O_3 based UMA and compared finishing characteristics of Magnesium alloy, Stainless steel, Brass plates and found that MRR of magnesium alloys is larger than brass and stainless steel. Deburring efficiency considerably increases with vibration assistance. Yan et al [10] and Amineh et al [11] applied MAF process to remove the recast layer and micro-cracks on EDM machined surface by using SiC-based UMA from tool steel cylindrical bar and aluminum alloy specimen. Wang [12] et al established that polishing speed, magnetic abrasive supply, abrasive material, magnetic abrasive manufacturing process and grain size have critical effects on the material removal rate (MRR) in MAF process.Singh et al [13, 14, 15] examined the microscopic changes in the surface texture and found that magnetic flux density and machining gap are the most influencing parameters for finishing of Alloy steel plane surface by using SiC-based UMA. Kim et al [16, 17, 18] studied finishing of thenonmagnetic AZ31 material plate and Al/SiC composite with MAF and found that surface roughness of plate improves with theinstallation of a permanent magnet under the workpiece. It is found that MAF is useful to remove the burrs on Magnesium alloy AZ31 plate without damage from its original surface. Mulik et al [19]obtained surface roughness as low as 51 nm in 120s machining time of Steel AISI 52100by finishing with MAF process using SiC-based UMA. Givi et al [20] studied MAF by using UMA and found that a number of cycles and working gap are the most significant parameters on surface roughness change (ΔRa) of Aluminum alloy. Saraeian et al [21] optimized machining parameters for finishing of outside surface of Stainless steel AISI 321 cylindrical surface by using SiC-based UMA and obtained minimum surface roughness through working gap of 1mm, workpiece rotational speed of 500rpm, and abrasive particle size of 100mesh.

2.2.2 Hybrid approach

A *hybrid approach* integrates the MAF process with another non-conventional machining process in order to improve its finishing characteristics.

Yan et al [22] developed Electrolyte Magnetic Abrasive Finishing (EMAF) process for finishing of outside surface of cylindrical SKD11 steel rods by using Al_2O_3 based UMA and established that EMAF process yields better finishing characteristics than MAF. El-Taweel et al [23] developed a hybrid Electrochemical Turning (ECT) based MAF process for finishing of Al/Al_2O_3 composite bars by using Al_2O_3 based UMA and found that MAF, assisted with ECT, leads to an increase in machining efficiency and resultant surface quality of workpiece. Jain et al [24] developed FMAB pulsating by using pulse direct current (DC) power supply and found that surface finish of Alloy steel plane surface enhanced many folds as compared to the surface finish achieved by the use of DC power supply. Mulik et al [25, 26, 27] developed UAMAF which integrates the use of ultrasonic vibrations and MAF process to finish Steel workpiece by using SiC-based UMA and found that Normal forces are lower and cutting torque is greater as compared to magnetic abrasive finishing. A mirror-like surface can be obtained using ultrasonic assisted magnetic abrasive finishing. A mathematical model was developed for temperature distribution at workpiece-magnetic brush interface for different processing conditions. Judal et al [28, 29] presented the machining performance of cylindrical electrochemical magnetic-abrasive machining [EC MAF] for high efficiency machining of stainless steel cylindrical surfaces by using SiC-based UMA and found that workpiece rotational speed and electrolytic current have a significant influenceon MRR and Ra. Judal et al [30] developed vibration assisted cylindrical–magnetic abrasive finishing (VAC–MAF) setup and investigated various process parameters by using Al_2O_3 based UMA for finishing of Aluminum cylindrical surface. Liu et al [31] developed EMAF set up and carried out finishing of Al 6061 plane surface by using SiC-based UMA and found that EMAF process is able to obtain better surface quality and higher material removal compared to traditional MAF.Kala et al [32, 33] developed a double disc MAF setup for finishing of aplane surface and carried out finishing of copper alloy, a paramagnetic material, by using Al_2O_3 based UMA. It was discussed that addition of a permanent magnet beneath the workpiece raises the MFD within the gap which increases the machining force acting on the workpiece and addition of ultrasonic vibration to workpiece improved the surface finish.Amineh et al [34] developed a new setup by combining MAF and ultrasonic floating abrasion process. Ultrasonic vibrations are provided to thepermanent magnet, attached to thehorn and put inside the tube for finishing. The finishing zone components are immersed in water to take advantage of cavitation collapse pressure.

2.2.3 Workpiece of smaller diameter

While finishing rods ofsmaller diameter it becomes imperative to retain its roundness.

Im et al [35] studied the finishing of stainless steel rod of Φ3 by using diamond based UMA and achieved a surface roughness as fine as 0.06 μm(Ry) and roundness as fine as 0.12 μm(LZS). Mun et al [36] studied the finishing of Tungsten Carbide rod of Φ3 with MAF process by using diamond based UMA and obtained roundness up to 0.15 μm.

2.2.4 Industrial Applications

MAF process is applied to finish some of the following industrial products:

Karpuschewski et al [37] developed an MAFset up to finish HSS twist drill and presented, in detail, the changes in microgeometry of cutting edges and the surface quality.Yamaguchi et al [38] carried out the internal finishing of steel capillary tube of dimensions Φ1.27mm × Φ1.06mm ×100mm with MAF process by using Al_2O_3 based UMA. A special tool was developed that exhibited alternating magnetic and nonmagnetic regions. Magnetic abrasive is attracted to the borders of the magnetic regions of the developed tool to create additional finishing points. Furthermore, the multiple pole-tip systems facilitated simultaneous finishing multiple sections with a short pole stroke. Kanget al [39] carried out finishing of internal surfaces of stainless steel capillary tube by using Al_2O_3 based UMA.Yamaguchi et al [40] carried out MAF process to finish AlTiN-coated round tool by using diamond paste and it was found that the roughness of coated tools was improved by 50–60% without deteriorating the cutting edge radius. Nteziyaremye et al [41] developed an MAF setup for simultaneously finishing of inside and outside surface of stainless steel needles by using Al_2O_3 based UMA and 0.4–0.5 µm R*a* was improved to 0.01 µm R*a* in 5 min.

2.3 Bonded Magnetic Abrasives (BMA)

Unbonded Magnetic Abrasives are easy to prepare but during finishing of workpiece some of the abrasive particles trappedin the valleys of surface and do not take part in thefinishing process. Literature survey proposes another category of magnetic abrasives, prepared by bonding abrasive particles with ferromagnetic particles, called as Bonded Magnetic Abrasives (BMA). In the literature, two types of methods of preparation are found; i) Sintering and ii) Mechanical alloying as shown in Fig 2 and one of the research studiescompared the performance of BMA with UMA through detailed experimentation. All these aspects are discussed in the following section:

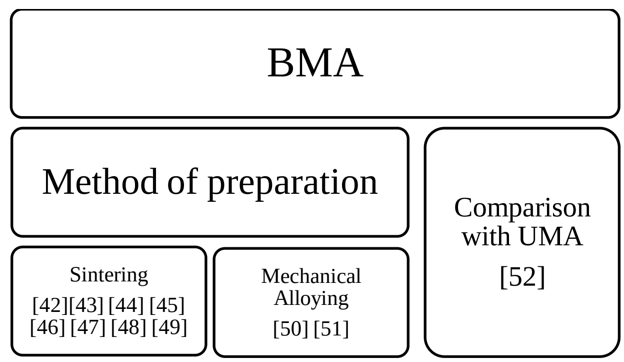

Fig 2: *Bonded Magnetic Abrasives as in Literature*.

2.3.1 Methods of preparation of BMA

2.3.1.1 BMA prepared by Sintering

Ahmed et al [42] prepared Al_2O_3 based BMA by sintering technique for finishing of silver steel bars and obtained surface roughness (Ra) in the range of 8-50nm in very short time, i.e., 20-180s. Mori et al [43] explained the mechanism of formation of magnetic abrasive brush in MAF process for finishing of stainless steel disc by using BMA prepared by sintered technique.Jayswal et al [44] developed a finite element model by consideringAl_2O_3 based sintered magnetic abrasives to evaluate the distribution of magnetic forces on the stainless steel workpiece.Girma et al [45] prepared Al_2O_3 based BMA for finishing of stainless steel plate and found that the surface finish improves significantly with an increase in the grain size, therelative size of abrasive particles vis-a`-vis the iron particles, feed rate and current. Lin et al [46] obtained a mirror like surface finish (as low as 0.102 µm) with BMA prepared by sintered technique in MAF process.Yang et al [47] prepared Al_2O_3 based BMA by sintered technique for finishing of AISI304 stainless steel plane surface and obtained mirror like surface finish(Rmax = 0.1 µm). Kumar et al [48] studied temperature distribution in themagnetic abrasive brush by using Cr_2O_3 based BMA for finishing of theinternal surface of Silicon nitride tube. It was found that temperature increases from bottom to thetop of theworkpiece and it increases with increase in circumferential speed.Hung et al [49] developeda system for prediction of surface finish of stainless steel tube for the development of adaptive control system that seeks to enhance the surface finish of parts in order to meet customer requirements and increase productivity by using Al_2O_3 based BMA.

2.3.1.2 BMA prepared by Mechanical Alloying

Sran et al [50] presented a new technique for preparing BMA called mechanical alloying. Mechanical Alloying (MA) is one solid state powder processing technique involving repeated welding, fracturing, and rewelding of powder particles in a high-energy ball mill orAttritor. These magnetic abrasives were used to finish internal surface of commercially available brass tubes and obtained a surface finish as low as 3 nm.Patil et al [51] prepared SiC-based BMA with mechanical alloying technique to finish inner surface of stainless steel tube and obtained the best surface finish at 10 gm abrasive amount, 0.5 gm of lubricant and a rotational speed of workpiece of 800 rpm.

2.3.2 BMA vs UMA

Liu et al [52] compared the performance of BMA and UMA in MAF process by using Al_2O_3 based magnetic abrasives and found that magnetic properties of the BMA are superior to UMA. BMA gives better finishing characteristic than UMA as shown in a bar graph,Fig 3. The bar graph shows that, for BMA,Average Surface Roughness declines with machining time and a minimum value israpidly obtained after 20min. On the other hand, for UMA, thesame level of Average Surface Roughness is obtained slowly after 40min. Thus, the finishing efficiency of the workpiece finished with BMAis double than the UMA.

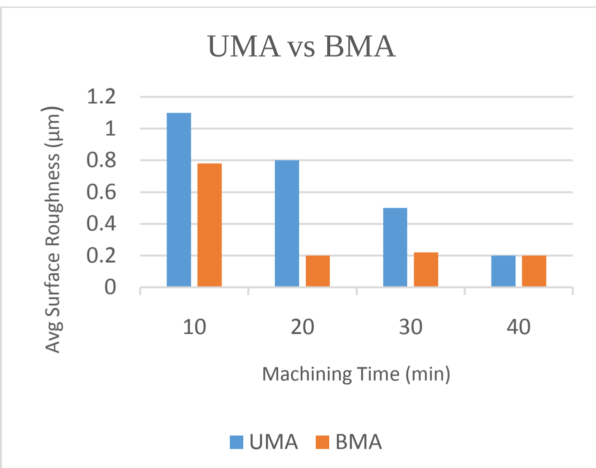

Fig 3: *Surface roughness of P20 steel by using Al_2O_3 abrasives.[The values of Avg Surface Roughness areapproximate valuestaken from Liu et al [52]]*

Remarks1:It has been observed that coated layer of Coated magnetic abrasives getsworn out from the magnetic particle while in theprocess, thus disturbing the finishing performance. The UMA is easy to prepare and hence most of the researchers used this technique for preparation of magnetic abrasives. It has been observed that most of the research studies have been focused on enhancing the capabilities of MAF process by using UMA,refer Fig 1. To enhance the capabilities of MAF process some of the authors proposed 'Hybrid approach' in which MAF process is integrated with other non-traditional machining processes like ECM, USM etc. It has been experimentally proved that 'Hybrid approach' improves machining capability in term of MRR and surface finish of workpiece. Furthermore, authors carried out research to study the role of MAF process in finishing industrial products like twist drill, acapillary tube, and stainless steel needle. As abrasives are not bonded to ferromagnetic material in UMA so abrasives are easily flown away by the centrifugal force during machining process and also abrasives, if trapped in the valleys of theworkpiece surface, do not take part in thefinishing process.To overcome this problem, theresearchershassuggested another technique of preparation of magnetic abrasives, called as Bonded Magnetic Abrasives (BMA), in which abrasive particles are bonded to ferromagnetic particles. In the literature, two types of techniques for preparation of magnetic abrasives has been found; i) Sintering technique and ii) Mechanical alloying, refer Fig 2. These techniques of preparation of BMA has been discussed in the literature and it has been stated that BMA give better finishing efficiency than UMA (Fig 3) but their technique of preparation is rather cumbersome and costly.

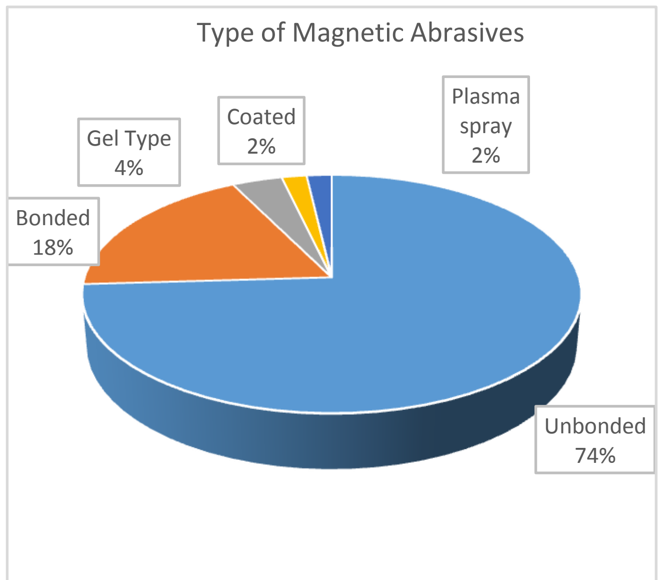

Fig 4: *Research studies on different type of Magnetic abrasives*

Literature review, based on the collected papers, show that 74% of the authors used unbonded magnetic abrasives (UMA) and 18% of the authors used bonded magnetic abrasives (BMA) as shown in Fig4.

2.4 Gel Abrasives

Wang et al [53] introduced anew method of preparation of magnetic abrasives by mixing the abrasives with silicone gel. This technique is neither costly & cumbersome like BMA nor are abrasives flown away by centrifugal force as in thecase of UMA during thefinishing process. Surface roughness reduction in MFGA was 3 times of surface roughness reduction in MAF. Wang et al [54] studied polishing efficiency and self-sharpening characteristics of Gel abrasives for finishing of outside surface of thecylindrical workpiece. Tsai et al [55] optimized the machining parameters for magnetic abrasive finishing with gel abrasives [MFGA] and stated that concentration of steel grit, machining time and kinds of abrasive dominate the behaviors of MFGA process.

2.5 Magnetic abrasives prepared by Plasma spray

Hanadaet al [56] developed spherical shaped magnetic abrasives with plasma spray for internal finishing of capillary tubes. The magnetic abrasives with irregular shaperesults in non-uniform cutting depth onthe workpiece surface. In this study,it is proposed to develop spherical shaped magnetic abrasives with less than 10 µm, which carries diamond particles as abrasive grains on the surface.

Remarks2:As discussed in *Remarks1*,abrasives are not bonded to the ferromagnetic material in UMA and hence these abrasives are easily flown away with the centrifugal force during themachining process. On the other hand,BMA, although gives better finishing efficiency than UMA but thetechnique of preparation is rather cumbersome and costly. So, the researchers proposed another technique of preparation of magnetic abrasives, called Gel abrasives, which alleviate the above-mentioned abrasive media problems. Gel abrasives utilize polymer gel to bond the ferromagnetic particles and abrasives. It was found that Surface roughness reduction with Gel abrasives was 3 times of surface roughness reduction with UMA.

Magnetic abrasives prepared with plasma spray is a special technique to give spherical shape to particles. Spherical shaped magnetic abrasives give uniform depth of cut and hence provide auniformsurface finish of the workpiece. These magnetic abrasives are especially useful to polish the internal surface of thecapillary tube.

Remarks3:In "*Remarks1*' and '*Remarks2*' different techniques of preparation of magnetic abrasives has been discussed with respect to their usages and shortcomings. Whilst going through literature it has been realized that there are some other aspects which effect the finishing characteristics of theworkpiece and hence needs special attention. These aspects are;type of abrasives, theshape of theworkpiece, and selection of abrasives in relation to workpiece material. Following discussion give an insight into these aspects of MAF process.

Different type of abrasives found in the research studies are Al_2O_3, SiC, Boron nitride, Chromium oxide and Diamond. Literature survey shows that45% of authors used Al_2O_3 abrasives, 36% of authors used SiC and 10% of the authors used diamond abrasives as shown in Fig5.

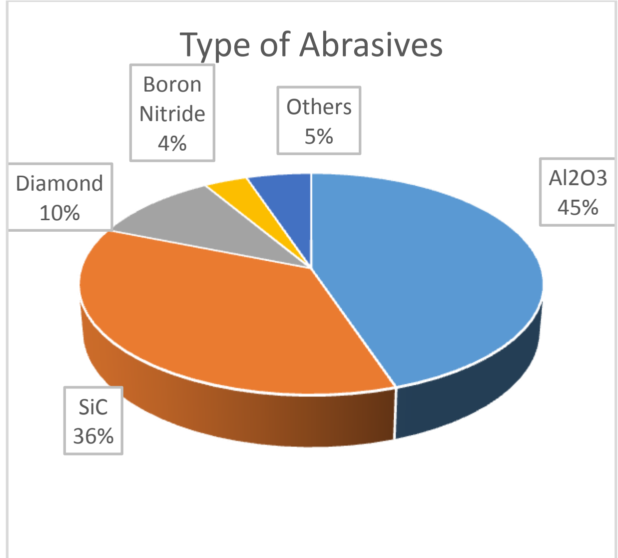

Fig 5: *Type of abrasives in literature.*

The design of MAF set up greatly depend upon the shape of theworkpiece. Review of research studies shows that (Fig6) 45% of the authors worked on plane surfaces, 30% of authors'machined

outer surface of thecylindrical bar and 23% of authors machined inner surface of thetube. A few researchers carried out finishing of industrial products like twist drill, the capillary tube, and stainless steel needles.

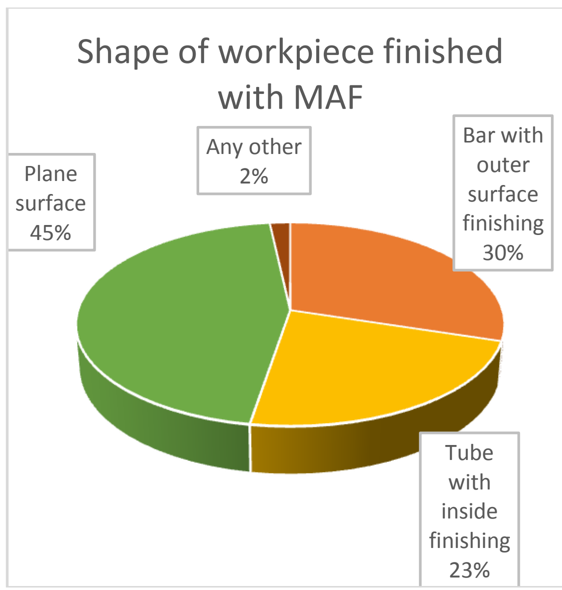

Fig 6: *Research studies on a different type of workpiece shape.*

The selection of abrasive materialis governed by the selection of workpiece material. Fig 6 shows the selection of abrasives in relation to workpiece material. In most of the research studies, Al_2O_3 and SiC abrasives have been selected for machining of metals and alloys and diamond abrasives have been used for machining of ceramics.

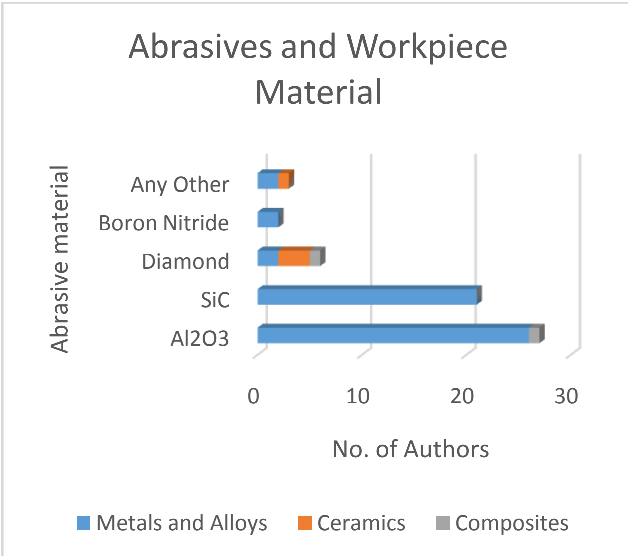

Fig 7: *Selection of abrasives in relation to workpiece material*.

3. MODELING AND SIMULATION OF MAF PROCESS

There are so many input parameters which influence the MAF process. Mathematical modeling and simulation are employed to predict the output of the process, mainly, the surface finish, temperature, and MRR under the influence of input factors.

Kremen et al [57] developed an empirical expression to estimate the machining time for mild steel cylindrical workpiece to produce a specified roundness. The expression has been validated through a series of experiments. Kim et al [58] developed a mathematical model to predict surface roughness of stainless steel tubes as a function of machining time for MAF process. Simulation results were compared with experimental results of previous papers. Kim et al [59] simulated the finishing force and the tool driving force for internal finishing of rectangular tubes from the simplified magnetic

*Remarks 5:*Fig 8 shows progress in the research trends of MAF process. Initially, researchers worked for the development of machining setups for finishing of different shapes/materials of workpieces and optimization of machining parameters of the process. In the year 2003 and onwards research area went broader when researchers start working on thehybridapproach of MAF with ECM and Ultrasonic Vibrations. Furthermore, in the year 2009 and onwards, researchers opened new avenues of research by studying the role of MAF for finishing of industrial products.

4. CONCLUSIONS

1. Different techniques of preparation of magnetic abrasives are Coated type, Unbonded, Bonded, Gel type and Plasma spray. Most of the research studies, 74%, preferred theunbonded or simply mixed type of magnetic abrasives.
2. Coatedmagnetic abrasives give good finishing characteristics but it has been observed that coated layer of abrasives gets worn out from the magnetic particle while in theprocess, thus disturbing the finishing performance.

circuit model for the finishing system. Jayswal et al [45] proposed a theoretical model for material removal and surface roughness and developed a finite element model of the process to evaluate the distribution of magnetic forces on the stainless steel workpiece surface by considering Al_2O_3 based BMA. Judal et al [60] simulated cylindrical electro-chemicalmagnetic abrasive machining (C-EMAM) process and simulated results were found to agree with experimental observations. Mishra et al [61] developed a model and simulated magnetic field distribution, magnetic pressure and temperature distribution at thework-brush interface for finishing of aplane surface. The developed simulation results based on FEA have been validated with experimental findings.

Remarks 4*:* Modeling and simulation techniques helped us to understand the mechanism and predict the output of the MAF process under the influence of input parameters. The modeling was first introduced in 1994 by Kremenwho developed an empirical expression for estimation of machining time to achieve specified roundness. After that, various studies were introduced to predict surface quality, cutting forces, thetemperature in MAF process.

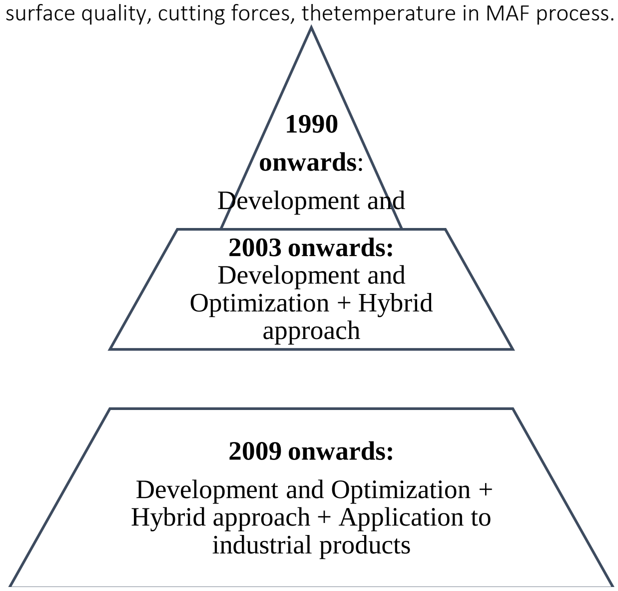

Fig 8: Progress in research of MAF process

3. The UMA is easy to prepare and hence most of the researchers used this technique for preparation of magnetic abrasives. Most of the research studies with UMA were focused on enhancing the capabilities of MAF process with an addition of the 'Hybrid approach' and the 'application of the MAF to industrial products'. UMA gives, relatively, low finishing efficiency.
4. The Bonded Magnetic Abrasives (BMA), although cumbersome and costly to prepare but give almost double finishing efficiency than UMA.
5. Gel Magnetic abrasives are prepared to get rid of the problems associated with the UMA and BMA. Surface roughness reduction with Gel abrasives is three times of surface reduction with UMA.
6. Plasma spray technique has been used to prepare spherical shaped magnetic abrasives. These magnetic abrasives give uniform cutting depth of the workpiece surface and found to be suitable for finishing of theinternal surface of capillary tubes.
7. Different types of abrasives found in the literature are Aluminum oxide, Silicone carbide, Diamond, Boron nitride and Chromium oxide. Most preferred abrasive is anAluminum oxide. 45% of researchers used this abrasive.

8. Aluminum oxide abrasive is mainly used for finishing of Metals and alloys whereas diamond is preferred for finishing of ceramics.
9. Different authors studied the finishing of different shapes of work pieces like outer surface of thecylindrical bar, theinner surface of tube and plane surface. Most of the authors, about 45%, carried out research on thefinishing of aplane surface.
10. A few authors developed amathematical model for temperature distribution, forces, and torque in MAF process and simulated the process.
11. One of the disadvantages of MAF is its low MRR. This disadvantage has been overcome by adopting ahybrid approach. Two types of hybrid machining have been found in the literature. In the first type MAF process has been integrated with ECM process and in the second type, MAF has been integrated with Ultrasonic vibrations.
12. MAF has been found to be successfully used for finishing of industrial products like along capillary tube, twist drill, and stainless steel needles.
13. Research area in MAF is going broader with theadditionof hybrid approach (2003 and onwards) and application to industrial products (2009 and onwards).

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