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Effect of magnetic abrasive finishing with steel balls on the surface improvement of Aluminium alloy

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Abstract

The magnetic abrasive finishing process (MAF) is a superfinishing process and has many merits over the traditional one. The majority of research conducted utilized ferromagnetic materials with abrasive particles to perform finishing for various materials. This study aims to investigate the effectiveness of hard steel balls such as ferro-magnetic abrasives in finishing AA 1100 aluminium flat alloys. Three parameters were selected with three levels as independent MAF inputs, namely: rotational speed (270, 600, 930 rpm), current (0.5, 1, 1.5 Amp), and finishing time (6, 9, 12 min.). For the purpose of comparison, the same parameters and levels were applied for traditional MAF, using a mixture of iron powder and tungsten carbides having a mesh size of 320 and 200 µm with equal ratios. The performance of the process was evaluated based on the improvement in surface roughness. Taguchi method with L9 orthogonal array was applied to investigate the influence of controllable parameters on the achieved surface roughness. The results revealed the superiority of MAF with steel ball over traditional MAF. The maximum surface improvement (ΔRa) was 0.082 µm for steel ball compared with 0.054 µm for traditional MAF. Rotational speed was the most significant parameter for both processes. The most significant parameter for both processes was the rotational speed with high contributions of 89.06% and 88.42% for both processes.

Keywords

Magnetic abrasive finishing, Steel balls, Aluminium alloy, Surface roughness.

1.Introduction

Modern manufacturing technologies require ultra-surface finish of engineering materials up to the nanometre level in different applications in industrial sectors. Important parts utilized in critical applications require an ultrafine surface finish. Good surface finish can be obtained using different finishing processes like grinding, honing, and lapping [1, 2]. However, such processes have certain demerits in finishing some advanced engineering materials such as difficulties in setting up fixtures and low accuracy for complex parts [3].

Currently, magnetic abrasive finishing (MAF) plays a significant role in finishing various parts and materials, even in miniature size and various geometries [4].

The MAF operation is a material removal process in which the accurate finishing is done via relative movement between generated magnetic brush and work part with the presence of a magnetic field in the finishing area [5]. MAF has a number of merits over traditional finishing methods. It is a non-conventional precision machining technology that uses magnetic force and ferromagnetic abrasives to perform the finishing process [6]. It began as a developed machining method in the United States in the 1930s, but it was not further refined until the 1960s [7]. Sharma and Singh addressed MAF in a patent in 2013[8]. MAF has been developed as a new finishing technology in the recent decade, especially for the fabrication of very precise and sensitive instruments for optical, medical, engine parts, and electrical components [9], but it is still a worthwhile and practical machining procedure. The possibility of damage occurring is minimized in MAF process due to low level of cutting forces and loose abrasives are utilized that enabled MAF to finish small, sensitive, and high technology parts with complex and different

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geometries. Furthermore, this process is characterized by: low power utilization, easy to perform, friendly for the environment, processing of different materials, lower thermal stresses, improvement of mechanical properties, adaptable and controllable [10]. The flexible magnetic brush (FMAB) is created once the controllable current is applied that generate a magnetic field. The brush consists of ferromagnetic powder and magnetic, abrasive particles [11]. Different configurations of MAF have proposed due to fact that MAF process has ability to finish free form surface, external and internal surfaces, but the mechanism of material removal is the same [12]. The schematic configuration of MAF in the simplest form is shown in *Figure 1* in which the south pole is working part fixed to a holder while magnetic pole is the north pole and the gap between those poles are filled with ferromagnetic-abrasive powders to act as FMAB during applying current [13]. It is also utilized in finishing flat surface as well as internal and external round surfaces. Furthermore, MAF acquired numerous benefits due to several advantages like: the process parameters are controllable; it is self-adaptable process, environmental friendly, the thermal defects are eliminated with MAF, and low power consumption [14].

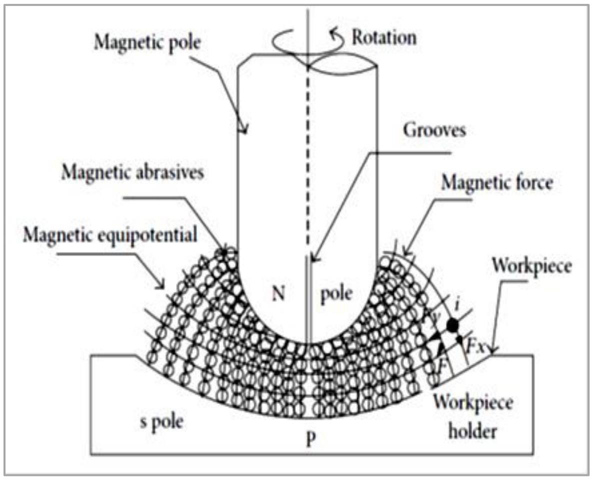

Figure 1 Configuration of MAF process [14]

The parameters of the MAF process are classified into two groups: (i) input process parameters like rotational speed, working gap, grinding oil, abrasive particles, applied current, abrasive particles, work piece material, finishing time, and geometry of pole and (ii) output process parameters which are usually refers to surface roughness and material removal. The first group is independent variables while second one is dependent responses.

When FMAB is generated, two forces are exerted: normal and tangential forces. The first force presses the brush against work part to form micro-indentation and due to rotation of FMAB, the second force performs material removal by micro-chipping. The magnitude of these forces is very small compared with the corresponding forces in traditional finishing processes.

The rest of the paper is organized in the following manner. Related work has been discussed in section 2. Section 3 covers the methods and complete working procedure. Results have been discussed in section 4. The result discussion has been presented in section 5. Conclusion and future work in section 6.

2.Literature review

Many researches and investigations were carried out to improve the performance of MAF in finishing different materials with various shapes. For example, the MAF finishing of the inner surfaces for three tubes made of brass, aluminum and stainless steel was evaluated by Wang et al. [15]. The material removal rate (MRR) was affected positively with increasing rotational speed and abrasive particle size from 30-50 % for TiC and 35% for Fe. The surface roughness of the tube was reduced to 0.24 µm from the original value of 9.6 µm. Kadhum et al. [16] investigated the impact of MAF on the surface quality of aluminum alloy. The performance of MAF was compared with grinding process. The result showed that MAF improved surface finish 1.5 to 2 times higher than grinding. Mahajan and Tajane [17] confirm in their study that surface improvement of ferromagnetic materials are highly affected by increasing rotational speed to certain optimum level because beyond that level, the abrasive particles start to fly away from the working zone due to high centrifugal force comes from high rotational speed.

Kadhum et al. [18] investigated the response of AA 7020 aluminium alloy and AISI 410 stainless steel to the MAF. The working gap, coil current, feed rate and powder volume were chosen as process parameters and Taguchi design of experiment was utilized to generate experimental runs. The result revealed improvement in surface roughness of both ferromagnetic and non-ferromagnetic materials. The surface roughness of the ferromagnetic was improved by 40-60% and was highly sensitive to working gap and current compared with other parameters while non-ferromagnetic materials recorded surface improvement of 30-40% which was sensitive to magnetic abrasive powder and working gap higher than other two parameters.

Qate'a and Mustafa [19] examined the influence of various poles geometries on the efficiency of the MAF process for the cylindrical part based on obtained surface finish and removal of material. The findings showed that these indexes were affected by Pole angles, working Gap, mesh size of magnetic, abrasive powder, weight of powder, applied current, workpiece speed, electromagnetic speed, and working time. The work piece rotational speed was the dominant contributor to the surface finish with 23.80% followed by other parameters.

Vahdati and Rasouli [20] investigated the controllable parameters of MAF represented by gap size, feed rate, rotational speed, and powder quantity on the free form finishing of aluminum surfaces. They used iron and tungsten carbide powders with a weight ratio of 2:1. The optimum values of gap, feed, speed, and powder weight were: 0.5 mm, 10 mm/min, 2100 rpm, and 1.75 g respectively.

Another study conducted by Singh and Kumar [21] to investigate the influence of finishing time and other MAF parameters on aluminum 6082 flat piece in terms of surface roughness. A mixture of iron and emery (black mixture of corundum and emery) magnetite was used as abrasive powder to perform MAF process. Their findings confirmed the significant effect of finishing time on the achieved surface roughness.

A newly developed media for magnetic, abrasive was investigated by Li et al. [22] in terms of achieved surface roughness (Ra) and MRR. The working medium was prepared in the semi-solid phase and the inner and outer surfaces of AA 6061 aluminum tube were finished by the MAF process. The results revealed improvements in both surface roughness and material removal where any increasing of process parameters such as rotational speed, ferromagnetic phase, mesh number of abrasive particles, and the mass ratio for main polymer led to achieve high amelioration of Ra and MRR with 96.67 % and 1.916 mg/ s respectively.

Also, Heng et al. [23] developed ultra-high-precision magnetic abrasive finishing (UPMAF) of steel wire with a diameter less than 0.6 mm. The selected variable parameters with three levels were; the rotational speed (350,600,800) rpm, the polycrystalline diamond (PCD) (0.5, 3.6) mm and finishing time (10, 60,120) seconds. The results showed that the new pole geometry with optimized parameters consisted of rotational speed: 800 rpm, diamond abrasive particle: 0.5 mm, and finishing time: 60 sec, maintained ΔRa of (0.23) μm.

In order to increase the surface quality of AISI 304 stainless steel flat plate, Xie and Zou [24] used an alternate magnetic field rather than a static field. In the alternating current, they employed sine and square waveforms. In two different electromagnetic waves, a variation in electromagnetic cluster oscillation behavior was observed and explored. The researchers concluded that employing a square wave causes the magnetic cluster to vary faster and that when the size of the magnetic particles decreases the difference in the magnetic cluster fluctuation speed between the two waveform increases. As per the measurements, the quality of the surface improved from 328 nm Ra to 14 nm Ra after 40 minutes.

Bae and Kim [25] developed UPMAF to improve the dimensional accuracy and surface quality of 625 Inconel circular cross-section bars. Ferro-polycrystalline diamond (FPCD) were magnetized with permanent magnets made of neodymium (Nd-Fe-B), and UPMAF was accomplished by using a 5-axis computer numerical machine (CNC). A rotatable and feedable workpiece at different rates, flux density, finishing time, and different abrasive sizes were chosen as input parameters. The machined surface was characterized by using a thermal imager, atomic force microscope (AFM), and energy dispersive X-ray analysis (EDX). As findings revealed, the range of surface roughness improvement (SRI) was 2010-200 nm at 12000 rpm, 2000 mm/min, 1 μm grain size, 300 mT flux density and 5 min finishing time.

Zhang and Zou [26] used a method to show the impact of the surface correction of work part surface by modifying MAF parameters such as feed speed at different positions across the profile of the initial surface. The method was theoretically analyzed and extended to involve applications to large scale areas based on the set of tests on AA 5052 Alloy, the geometrical precision of the surface being finished can be effectively regulated by manipulating feed speed. The results showed a large variation in work piece surface quality was enhanced from 4.81 m to 2.65 m within the finished region of 30 x10 mm^2.

Internal surfaces of thick AISI 304 stainless steel tubes were finished via a proposed MAF process by

Liu and Zou [27]. The surface roundness was improved via studying its mechanism theoretically through deriving the roundness curve based on roughness measurement principles and the center method. Then, the Fourier series was applied to expand and obtain the roundness curve formula. To verify the roundness formula, MAF experiments have been performed with the following parameters: tube thickness: 10,20,30 mm; magnet: Nd-Fe-B; workpiece speed: 162 rpm; magnet speed: 186 rpm; 1680 micron and 24 gm Electrolytic iron powder; 2.5 gm of #400, #3000, #6000, #10000 white alumina; finishing time: 15 min; and 30 gm of SCP-23 water-based grinding fluid. The results showed excellent improvement in roundness for 10 mm tube thickness versus very good enhancement for 20 mm tube and good roundness for 30 mm tube where the three tubes recorded roughness ranges of 172-22, 178-51, and 179-81 respectively. That means as tube thickness increases the roughness decreases.

To analyze the above literature review, it was found that MAF approved its capability as a non-traditional process to produce a high surface finish. Majority of performing works that have been done by MAF processes utilized at least two materials in powder form: ferromagnetic powder to generate a magnetic field and hard abrasive particles to preform finishing by the produced FMAB. The performance of MAF is highly affected by the combination of the two different materials in terms of the amount of powder, particle size, and mesh number in addition to other parameters. Hence, the better findings will be restricted with the best selection of combination beside the effect of other controllable variables.

Therefore, this research is an attempt to investigate the effectiveness of using steel ball as a replacement for the traditional magnetic abrasive due to two facts: it has a hard surface and at the same time it is ferromagnetic materials and thus, combine the two important effects of FMAB to perform finishing.

3.Materials and methods

The MAF of aluminium alloys was implemented in this work using a vertical milling machine (Turret milling). *Figure 2* depicts the milling machine with an assembled MAF unit. An induction coil, consisting of an iron core, with 20 mm in diameter and 150 mm in length, was fabricated. An inductive coil was made from 0.5 mm fine copper wire with 15,000 turns and attached from the top position with commutator which supplied with controlled direct current (DC) power supply. Magnetic pole was connected at the coil bottom. AA 1100 Aluminium alloy with 100 mm length, 50 mm width and 3 mm thickness has been used while alloy composition is shown in *Table 1.*

Hardened steel balls with a diameter of 4.5 mm were used in this work to study its effectiveness compared with traditional ferromagnetic abrasive particles which consists of iron powder and tungsten carbide particles with mesh sizes of 320 and 200 µm respectively. *Figure 3* depicts the magnetic pole with steel ball and magnetic abrasive particles. Rotational speed (rpm), current (Amp.) and finishing time (min.) were nominated to be investigated in this study with three levels as revealed in *Table 2* while other parameters were kept constant as shown in *Table 3.* Nine experimental runs were generated based on the L 9 array of Taguchi method as shown in *Table 4.*

The surface roughness tester (model SRT 6210) with a cut off 0.8 mm shown in *Figure 4* was utilized to measure final roughness. The measurements were taken along the finished surface at three different locations and averaged values were tabulated.

Figure 2 Milling machine with MAF unit

Table 1 The chemical composition of utilized alloy

Element	Al	Be	Cu	Mn	Zn	Si,Fe
Nominal	99 (minimum)	0.0008 (maximum)	0.05-0.2	0.05 (maximum)	0.1(maximum)	0.95 (maximum)
Experimental	99.3	<0.001	0.0596	0.0146	0.0339	0.361

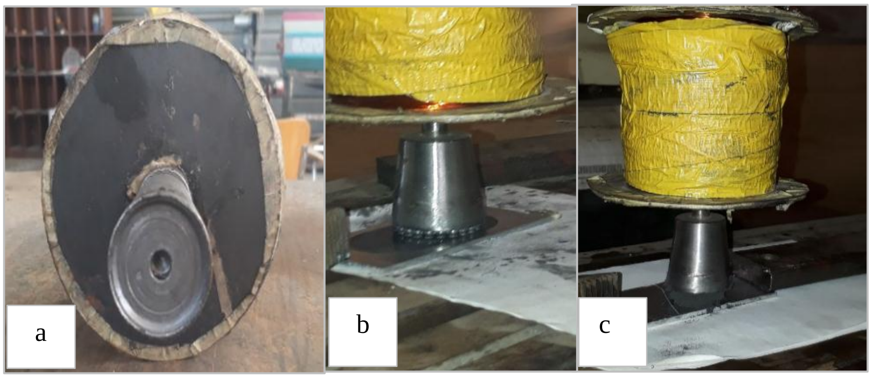

Figure 3 Magnetic poles, a. Magnetic pole, b. magnetic pole with steel balls, c. magnetic pole with magnetic abrasive particles (MAP)

Table 2 Process parameters

No.	Parameters	Unit	Sym.	L(1)	L(2)	L(3)
1	Speed	rpm	A	270	600	930
2	Current	Amp	B	0.5	1	1.5
3	Finishing time	min	C	6	9	12

Table 3 Constant parameters

No.	Parameters	Value
1	Work Piece Dim.	50 × 100 × 3 mm
2	Work Piece Material	Al
3	Rotational Direction	CCW
4	Room Temperature	20 Cº
5	Type of Abrasive	WC-iron
6	WC Mesh size	200 mesh
7	Iron mesh size	320 mesh
8	Ball diameter	4.5 mm
9	Voltage	220 V
10	Frequency	50 Hz
11	Working Gap	1 mm

Table 4 Orthogonal array with coded and real factors

	A-Code array			B- Orthogonal array		
No.	A Speed	B Current	C time	A Speed	B Current	C time
1	1	1	1	270	0.5	6
2	1	2	2	270	1	9
3	1	3	3	270	1.5	12
4	2	1	2	600	0.5	9
5	2	2	3	600	1	12
6	2	3	1	600	1.5	6
7	3	1	3	930	0.5	12
8	3	2	1	930	1	6
9	3	3	2	930	1.5	9

Figure 4 Surface roughness tester (SRT-6210)

4.Results

The experimental runs for both MAF processes (i.e MAF with steel balls and traditional MAF) were carried out and the corresponding results were tabulated and plotted to be discussed and analysed in this section. Each set of the two MAF parameters has generated different enhancement in surface improvement (ΔRa). Surface roughness improvement rate (SRIR) was calculated by using the following Equation 1.

$$\text{SRIR\%} = \frac{\text{Initial reading} - \text{Final reading}}{\text{Initial reading}} \times 100\% \tag{1}$$

Each of the above values (ΔRa and SRIR) was tabulated for steel ball and traditional MAFs as shown in *Tables 5* and *6*. Also the maximum and minimum values were recorded for both MAFs. In the next subsections, the findings will be discussed statistically based on the analysis of variance (ANOVA) results and regression model is going to be developed while the effect of process parameters on surface improvement for both MAFs will be analysed later on.

Table 5 ΔRa and SRIR of MAF with Steel Balls

No.	A Speed	B Current	C Time	ΔRa	SRIR
1	270	0.5	6	0.080	16.93
2	270	1	9	0.078	16.50
3	270	1.5	12	0.082	17.35
4	600	0.5	9	0.075	15.86
5	600	1	12	0.076	16.08
6	600	1.5	6	0.077	16.29
7	930	0.5	12	0.066	13.95
8	930	1	6	0.070	14.80
9	930	1.5	9	0.067	14.16
Max	-			0.082	17.35
Min	-			0.066	13.95

Table 6 ΔRa and SRIR of traditional MAF with steel balls

No.	A Speed	B Current	C Time	ΔRa	SRIR
1	270	0.5	6	0.052	10.98
2	270	1	9	0.054	11.40
3	270	1.5	12	0.050	10.55
4	600	0.5	9	0.028	5.878
5	600	1	12	0.023	4.816
6	600	1.5	6	0.019	3.966
7	930	0.5	12	0.016	3.329
8	930	1	6	0.017	3.541
9	930	1.5	9	0.012	2.479
Max	-			0.054	11.40
Min	-			0.012	2.479

5.Discussion

5.1Statistical Analysis of steel balls and traditional MAFs results

The ANOVA *Tables 7* and *8* were constructed for both processes. Both Tables reveal the significance of models with p-values of 0.004 and 0.006 for steel balls MAF and traditional MAF respectively. The most significant parameter is rotational speed based on its low p-value and high contribution which reached around 89.06% and 88.42% for both processes. In contrast, the other two parameters (i.e., current and finishing time) for both cases were not significant due to large p-values which were larger than 0.05 at confidence level of 95%. The linear regression models were developed for both processes using Minitab 17 to predict the roughness improvement as indicated in Equations 2 and 3.

$$\Delta \mathrm{Ra} = 0.08527 - 0.000019\mathrm{A} + 0.00167\mathrm{B} - 0.000167\mathrm{C} \qquad (2)$$

$$\Delta \mathrm{Ra} = 0.0679 - 0.000056\mathrm{A} - 0.00500\mathrm{B} + 0.000056\mathrm{C} \qquad (3)$$

To calculate the prediction accuracy of the above models, Equation 4 is utilized to determine the percentage error between real and predicted roughness values.

$$\%\ \mathrm{error} = \frac{|\mathrm{Experimental\ Ra} - \mathrm{predicted\ Ra}|}{\mathrm{Expermental\ Ra}} \times 100\% \qquad (4)$$

By replacing the experimental values of speed, current, and time in Equation 2 and Equation 3 as well as calculating the % error using Equation 4, *Tables 9* and *10* are produced.

Table 7 ANOVA results of ΔRa for steel balls MAF

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant parameter	Contribution %
Regression	3	0.000234	0.000078	17.41	0.004	_	_
A Speed	1	0.000228	0.000228	50.96	0.001	Significant	89.06%
B Current	1	0.000004	0.000004	0.93	0.379	Not significant	1.56%
C Time	1	0.000002	0.000002	0.33	0.588	Not significant	0.78%
Error	5	0.000022	0.000004	_	_	_	8.59%
Total	8	0.000256	_	_	_	_	100.00%

Table 8 ANOVA results of ΔRa for powder MAF

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Significant parameter	Contribution %
Regression	3	0.002091	0.000697	15.04	0.006	_	_
A Speed	1	0.002054	0.002054	44.31	0.001	Significant	88.42%
B Current	1	0.000038	0.000038	0.81	0.41	Not significant	1.64%
C Time	1	0	0	0	0.955	Not significant	0.00%
Error	5	0.000232	0.000046	_	_	_	9.99%
Total	8	0.002323	_	_	_	_	100.00%

Table 9 Experimental and predicted ΔRa with average % error for steel ball MAF

No.	Experimental ΔRa	Predicted ΔRa	% Error
1	0.079666667	0.079973	0.384518408
2	0.077666667	0.080307	3.399570372
3	0.081666667	0.080641	1.25591877

No.	Experimental ΔRa	Predicted ΔRa	% Error
4	0.074666667	0.073202	1.961607581
5	0.075666667	0.073536	2.815859459
6	0.076666667	0.075373	1.687391732
7	0.065666667	0.066431	1.163958877
8	0.069666667	0.068268	2.007655971
9	0.066666667	0.068602	2.902999485
Average			1.953275628

Table 10 Experimental and predicted ΔRa with average % error for traditional MAF

No.	Experimental ΔRa	Predicted ΔRa	% Error
1	0.052	0.050616	2.0335
2	0.054	0.048284	10.030
3	0.050	0.045952	7.4792
4	0.028	0.032304	16.761
5	0.023	0.029972	32.229
6	0.019	0.027136	45.371
7	0.016	0.013992	10.689
8	0.017	0.011156	33.064
9	0.012	0.008824	24.365
Average			20.224

The degree of matching between experimental and predicted roughness in steel ball MAF is higher than the corresponding degree of traditional MAF. This behaviour was reflected in the average percentage error where the first process recorded 1.953 compared with 20.224 in the second process. To visualize the degree of matching clearly, *Figures 5* and *6* is constructed for both processes.

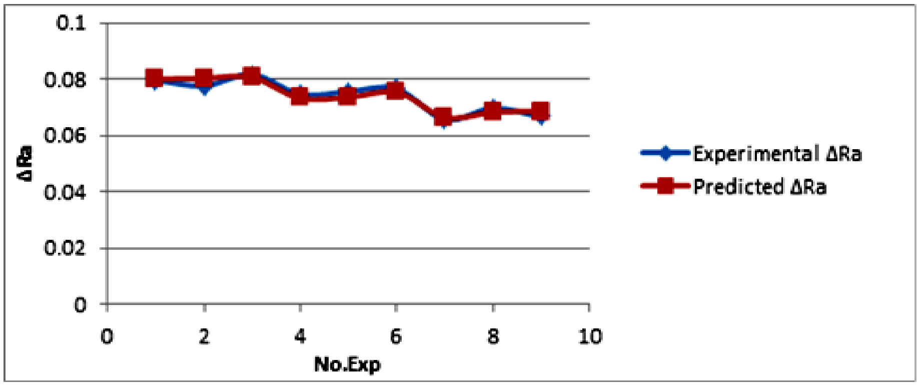

Figure 5 Experimental and predicted surface roughness (ΔRa) for steel ball MAF

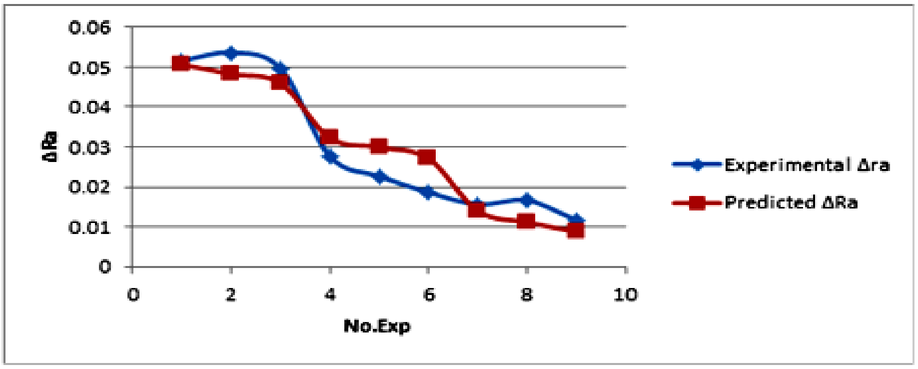

Figure 6 Experimental and predicted surface roughness (ΔRa) for traditional MAF

5.2Effect of magnetic abrasive parameters on the performance of steel balls and traditional MAFs

In the previous subsection, the statistical analysis of the achieved results was presented and ANOVA Tables identified the significant and non-significant parameters along with corresponding contributions. The effect of each input parameter on surface improvement will be analysed here and the performance of both processes is going to be assessed as well.

The main plot effects for means are useful tools to clarify the influence of input parameters on the surface improvement and therefore they adopted here as depicted in *Figures 7* and *8.*

Figure 7 shows the effect of the parameters on the surface roughness when using steel balls MAF process. It is obvious the significant impact of speed on the mean surface roughness as it decreases with increasing rotational speed more than 270 rpm particularly at 930 rpm. This may be attributed to the slight softening in steel ball hard layer due to friction with work piece during finishing that reduce the shearing action as well as high centrifugal forces that try to fly steel balls away from the magnetic pole. However, the differences in mean roughness between three rotational speeds are not so high as compared with *Figure 8*. With regard to the applied current, the enhancement of surface improvement can be viewed with increasing applied current but not to the significant level where the mean roughness values are near to the mean of mean (Ra). Pertaining the effect of time, its increasing from 6 to 9 minutes has reduced the surface improvement and then back increased to the mean of mean (Ra) at 12 minutes but less than the corresponding value at 6 minutes. Both of applied current and time are not significant parameters as confirmed by ANOVA result that means putting any of them at any level will not give high improvement in surface roughness as compared with rotational speed.

Figure 8 depicts the main effect plots of rotational speed, current, and time against the mean of Ra for traditional MAF. The behaviour of rotational speed is similar to the corresponding one in steel ball MAF in terms of reduction of surface improvement due to increasing of rotational speed from low to high level. But the differences among the mean of roughness's are relatively greater than the corresponding values in steel ball MAF.

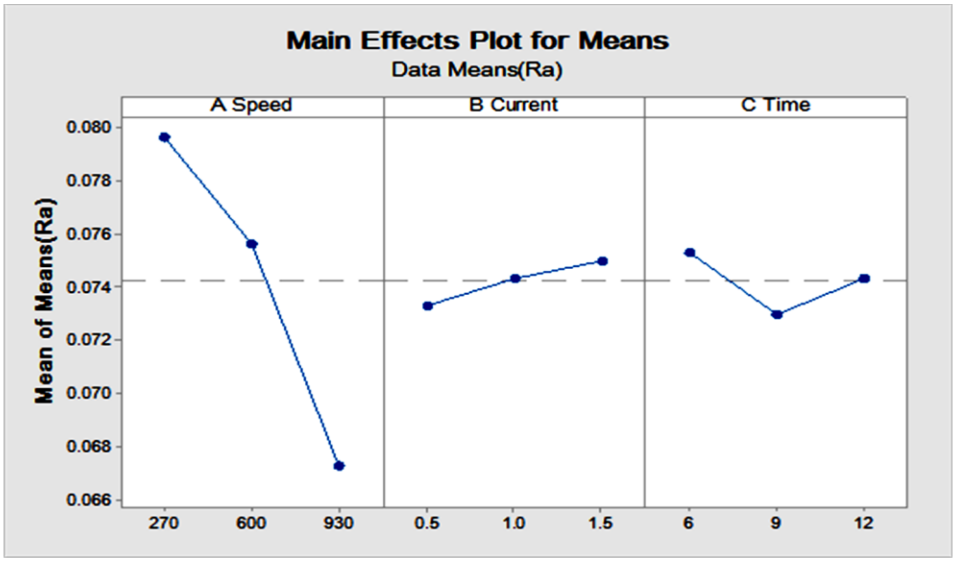

Figure 7 Main effect plots of the parameters verses mean ΔRa for steel balls MAF

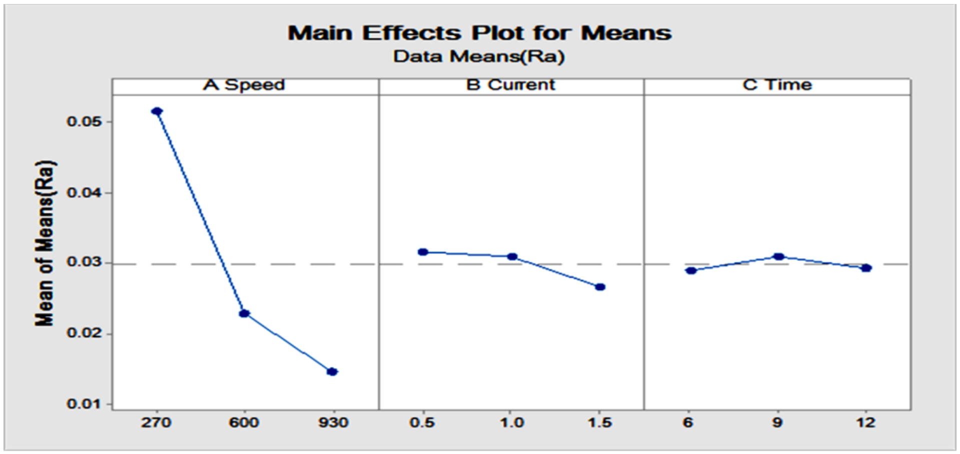

Figure 8 Main effect plots of the parameters verses mean ΔRa for traditional MAF

The effect of centrifugal forces increases at high level of rotational speed and it is more noticeable than steel ball MAF due to unbound nature of Ferro- abrasive particles in traditional MAF that causes loss of abrasive powder due to high centrifugal force and hence degrades the surface roughness.

With respect to the applied current, it is shown that increasing of current causes slight decrease in the surface improvement where it’s mean values have less fluctuation around the overall mean. Also, there is a small change in surface roughness against finishing time where slight increasing was achieved when prolonging time from 6 to 9 minutes and little reduction in roughness improvement at 12 minutes. To sum up, the current and time are not significant parameters as ANOVA result revealed and hence any change in their level will not affect the roughness improvement significantly.

In order to judge which of the implemented process is more superior, a column chart was constructed based on the experimental data in *Tables 5* and *6* as shown in *Figure 9*. The superiority of steel balls MAF is visible over traditional MAF particularly at low rotational speed of 270 rpm. The centrifugal forces promote detaching of un-bonded ferromagnetic abrasive particles and powder loss specifically at higher speeds and unlike steel balls that combine ferromagnetic and abrasive action at the same time which support their stability at high rotational speed. Therefore, there was a slight reduction in surface improvement with increasing rotational speed level in case of steel balls MAF. A complete list of abbreviations is shown in *Appendix I.*

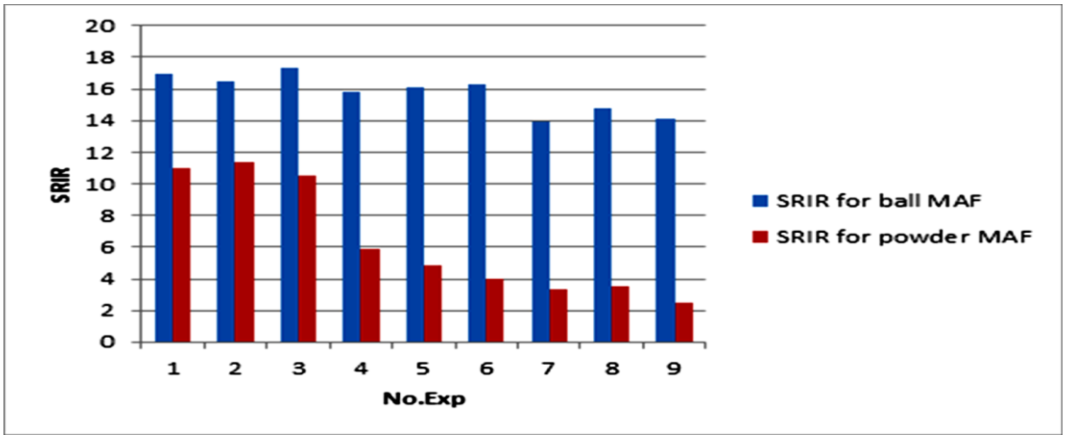

Figure 9 Comparison SRIR for steel ball and traditional MAFs

6.Conclusion and future work

The study investigated the effectiveness of using steel balls as hard and ferromagnetic materials at the same time and compares its performance with traditional MAF. According to the achieved results from the current conducted study, it can be concluded that the MAF, using steel balls proved its superiority over traditional MAF in finishing AA 1100 aluminium alloys in terms of SRIR as well as economic side where steel balls are cheaper than tungsten carbides and iron powders. Further, the surface improvement (ΔRa) was significantly influenced by rotational speed where low speed of 270 rpm achieved maximum ΔRa with 0.081667 µm and 0.053667 µm for steel balls and traditional MAFs respectively. Finally, the applied current and finishing time were not significant parameters and they did not produce a high improvement as compared with rotational speed for both processes.

Other researchers could consider the following recommendations for future work to get further improvement of MAF process:

1. Using newly made balls of various diameters and materials and testing their performance with MAF.
2. Investigate the influence of other parameters on the performance of steel balls MAF.
3. Develop an online adaptive control system that is able to perform online tuning for the controllable parameters.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Author’s contributions statements

Mariam Majeed: Conceptualization, investigation, data curation, writing – original draft. **Salah Al-Zubaidi:** Data collection, conceptualization, writing – original draft, writing – review and editing, analysis and interpretation of results. **Ali H. Khadum:** Study conception, design, supervision, investigation on challenges and draft manuscript preparation.

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Appendix I

S. No.	Abbreviation	Description
1	AFM	Atomic Force Microscope
2	ANOVA	Analysis of Variance
3	CNC	Computer Numerical Machine
4	DC	Direct Current
5	EDX	Energy Dispersive X-Ray Analysis
6	FMAB	Flexible Magnetic Brush
7	FPCD	Ferro- Polycrystalline Diamond
8	L9	Orthogonal Array
9	MAF	Magnetic Abrasive Finishing
10	MRR	Material Removal Rate
11	Nd-Fe-B:	Neodymium Permanent Magnet
12	PCD	Polycrystalline Diamond
13	Ra	Surface Roughness
14	SRI	Surface Roughness Improvement
15	SRIR	Surface Roughness Improvement Rate
16	UPMAF	Ultra-High-Precision Magnetic Abrasive Finishing
17	ΔRa	Surface Improvement