Experimental study of modified electro-chemical magnetic abrasive finishing of the magnetic cylinder

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Abstract

The nanometre level of surface finish is the main requirement in the manufacturing sector for high performance components. The use of advanced materials in precision components makes it difficult for finishing processes to achieve nanometre level of surface finish. Electro-chemical magnetic magnetic abrasive finishing (ECMAF) is a hybrid finishing technique that combines magnetic abrasive finishing and electro-chemical dissolution to finish extremely hard materials to the nanometre level. In this study, ECMAF is modified to minimize the issue of abrasive dragging and electrolyte short-circuiting, and it is tested with magnetic stainless steel (SS420). The working gap, electrolyte current, NaNo3 concentration, electrode gap, electrolytic flow rate, and workpiece rotational speed were all investigated for their effects on Surface Roughness (SR) and Material Removal (MR). Due to the high permeability of magnetic steel SS 420, SR decreases 17% more and MR rises 15% more than non-magnetic steel SS 304. Abrasion-assisted passivation increased MR by 73.91 percent and decreased surface roughness by 73.43 percent when compared to other constituent processes, indicating the process's feasibility.

Keywords: Electrochemical, magnetic, feasibility, modified, finishing, hybrid, synergy, abrasion, roughness

1. Introduction

The primary requirement for high responsive mechanical parts used in robotics, automation, and aerospace is a Nano level surface finish with no surface damage. Components associated with fluid flow also need high surface finish to reduce clogging of fluid. Such a parts are made of advanced engineering materials with high hard surface cannot be finished by conventional finishing process (Benardos et al, 2003). Abrasive flow finishing, magneto-rheological finishing, magneto-rheological abrasive flow finishing, magnetic abrasive finishing (MAF), electrochemical dissolution (ECD), and electrochemical magnetic abrasive finishing (ECMAF) are modern processes used for micro/nano level finishing of components made of advanced engineering materials. Various researchers developed and applied these processes to mitigate the specific demands of the modern grinding industries (Jain, 2013; Jha & Jain, 2006; Heng et al., 2022; Dixit et al., 2021; Karthikeyan et al., 2021; Li et al., 2021; Dhull et al., 2021; Farwaha et al., 2020; Hu at al., 2020). One or more process are combined with abrasive abrasion to make hybrid abrasion process which eliminate the limitations of constituent processes and enhance the finishing performance. ECMAF is such hybrid finishing process that speed up the finishing of difficult to finishing materials by passivation-abrasion synergism (Judal & Yadava, 2013)

Yan et al. (2003) investigated the effect of electrolytic current and workpiece rotating speed on SR and MR. They discovered that as electrolytic current and workpiece rotation speed increase, so does SR. When the workpiece rotates slower and the electrolytic current is higher, steel grit particles are drawn out of the working gap and gathered in the electrode gap, resulting in an electrolytic short-circuiting problem that halts the finishing process. By integrating electrochemical turning with MAF, El-Taweel (2008) designed the electrochemical turning-MAF setup and carried out studies using RSM. He examined the magnetic field effect of the MAF on the electrolysis of the ECD. He highlighted that Lorentz's force alters the ions' path and boosts ionic mobility in the electrode gap, improving the efficiency of the process. Wu and Yu (2015) developed the plane ECMAF setup to finish the polycrystalline silicon plane work surface. They experimented with the L18 orthogonal array and discovered that the magnetic force reduces bubble accumulation in the electrode gap and efficiently removes surface defects in a short period of time. Zou and Sun (2018) developed the ECMAF setup innovatively with a compound processing tool to finish the plane surface of the SUS304 workpiece. Singh et al. (2021) performed experimentation to analyze the work surface's surface temperature and used FEM based model to predict the temperature and magnetic flux density in the working gap. Jain et al. (2008) used an electromagnet with pulsed D.C. power to shape and distort the FMAB in the working gap. They determined that the pulsing current outperforms the direct current by observing the variable's effect on SR, indentation force, cutting force, and forces ratio. Girma et al. (2006) installed MAF attachment on the milling machine, performed experiments using RSM to finish the plane surface, and obtained a 54% reduction in SR. They observed that with smaller grain size, more current, and faster feed rate, the surface finish improved. Singh et al. (2022) used the genetic algorithm to optimise process parameters for chemically assisted MAF for internal surface improvement, external surface improvement, and MR. They investigated process parameters and discovered that abrasive size and finishing time had the greatest impact on SR and MR improvement. Judal and Yadava (2013) created the ECMAF configuration by placing the copper electrode on top of the workpiece and the magnetic poles at a 180-degree angular position (Fig. 1(a)). They conducted experiments with the non-magnetic SS304 workpiece and found that MAF assists in the removal of the dissolved peaks and ECD contributes more to the MR. Fig. 1 displays the magnetic flux density for magnetic SS420 and nonmagnetic SS304 workpieces as measured with a digital gauss metre in the working gap. Because of its high permeability, the magnetic flux density in the working gap of SS420 was found to be higher than that of SS304. Because the ECMAF process's performance is largely dependent on magnetic permeability, finishing with magnetic stainless steel would provide a new path towards the efficacy of the modified ECMAF process.

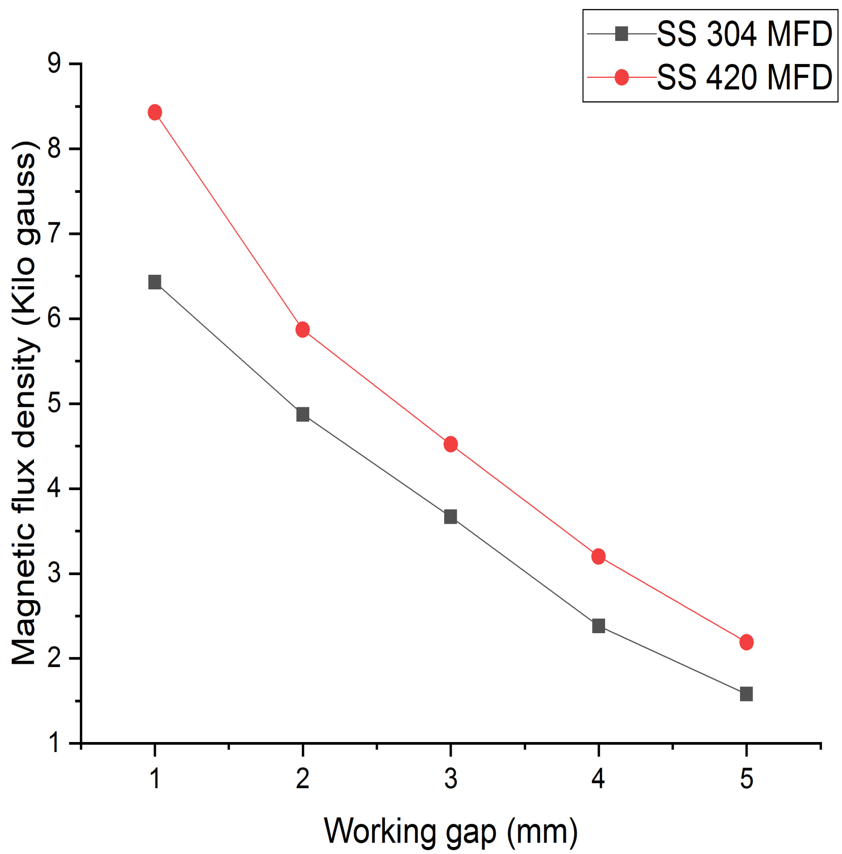

Fig.1. Magnetic flux density for the SS304 and SS420 workpieces at various working gaps

The current study focuses on the magnetic stainless steel (SS420) workpiece experimentation on the modified ECMAF. On the SR and MR, the effect of the working gap, NaNo3 concentration, workpiece rotational speed, electrolyte flow rate (EFR), electrolytic current, and electrode gap was investigated. The feasibility of the modified ECMAF was investigated. The process performance of magnetic and non-magnetic steel was evaluated for SR and MR.

2. Materials and Methods

2.1 Modified ECMAF Process

The modified ECMAF process was developed and attached to the CNC lathe. Finishing issues, abrasive dragging and electrolyte short-circuiting exist with the older version of the ECMAF arrangement, as shown in Fig. 2(a) (Judal & Yadava, 2013; Yan et al., 2003). The magnetic poles and electrode orientations were changed to alter the ECMAF process configuration, as shown in Fig. 2. (b). The magnetic poles at a 90-degree angle on one side of the workpiece and the electrode at a 45-degree angle on the opposite side was set in order to prevent electrode gap short-circuiting and abrasive dragging problems within the "O" ring. Because of this change, the electrolyte falls on the opposite side of the magnetic pole and does not pass through the working gap during the process. As a result, abrasives do not wash away and abrasive concentrations do not change in MAPs. Because the electrolyte does not pass through the working gap, it does not carry the MAPs to the electrode gap, reducing the electrolyte short circuit. The magnetic flux density within the working gap increases as the magnetic poles move closer together in the rearrangement. The problems with abrasive dragging, short-circuiting, and low magnetization are reduced, which may improve process performance.

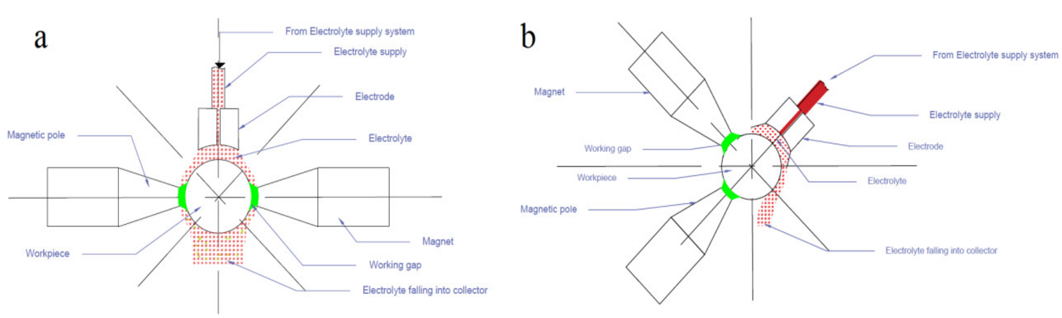

Fig.2. An illustration of an ECMAF setup shows (a) 180-degree poles and (b) magnetic poles and electrodes reoriented at 90 degrees and 45 degrees, respectively, on either side.

The details of the modified ECMAF setup are shown in Fig. 3. An "O" ring, permanent magnets, magnetic poles, electrodes, an electrolyte supply system, an electric contact brush, and a DC power source constitute the modified ECMAF setup. During the finishing, the "O" ring firmly places the electrodes, magnets, and magnetic poles. The copper electrode serves as both a cathode and a source of uniform electrolyte flow in the electrode gap. After being transferred from the NdFeB magnets, the magnetic flux density is concentrated inside the working gap by the magnetic poles. Filling the working gap with Magnetic Abrasive Particles (MAPs) results in the formation of a Flexible Magnetic Abrasive Brush (FMAB). The electrode receives electrolytes at the desired flow rate from the electrolyte supply system. The electrode receives cathode current from the D.C. power supply system, and the electric contact brush receives anodic current. It has a range of 0 to 5 A for current. The revolving workpiece receives anodic current from the electric contact brush while it maintains constant contact. The workpiece rotational speed is controlled using the CNC dashboard. Fig. 4(a) demonstrates the modified ECMAF components' assembly, and Fig. 4(b) depicts the photographic view.

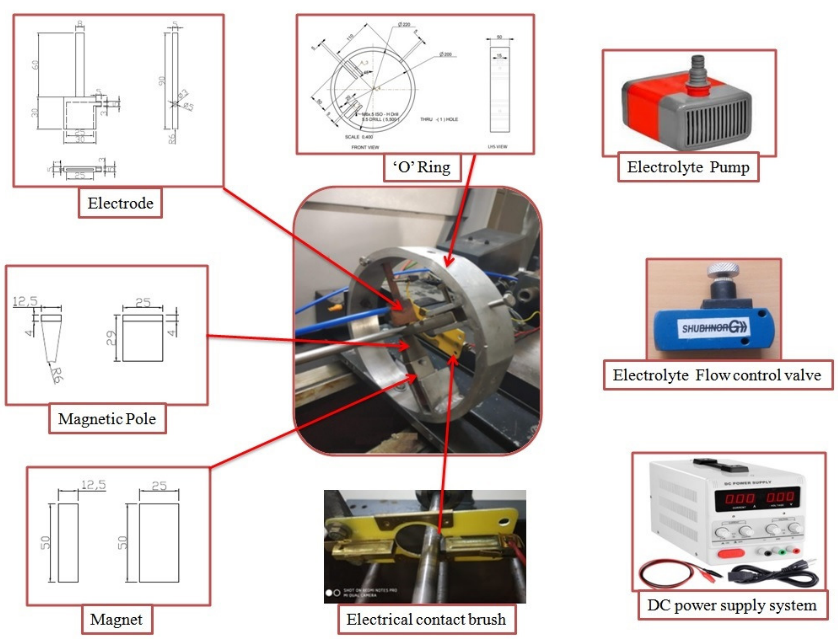

Fig.3. Details about the Modified ECMAF configuration

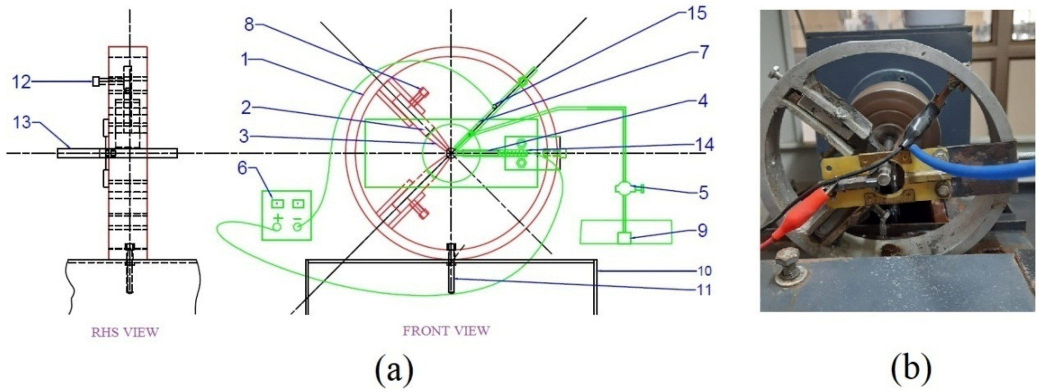

Fig.4. (a) Schematic illustration and (b) photographic picture of the modified ECMAF configuration

Note: 1. "O" ring 2. Strong Permanent Magnets 3. Magnetic poles with a high permeability 4. Brush for electrical contact 5. Control valve for electrolytic flow 6. DC power supply 7. Electrode with a hollow core 8. Adjustable working gap screw 9. a fluid pump 10. Base 11. Fixing screw for "O" ring 12. Adjustment screw for electrode positioning 13. Workpiece 14. Anode connection 15. Cathode connection

2.2 Experimental Procedure

Experiments were performed on an indigenously developed set up to analyse the finishing performance of modified ECMAF during the finishing of magnetic stainless steel (SS 420). The magnetic abrasives particles (MAPs), electrolytes, and workpieces were prepared for experimentation. The workpiece length was decided by considering chuck holding, "O" ring width, electric contact brush-width, and clearances. Due to superior finishing performance, iron particles were used as ferromagnetic, and SiC particles were used as abrasives (Judal & Yadava, 2013; Amnieh et al., 2017). The 2% SAE 30 oil was mixed with the MAPs to improve the particles bonding (Guo et al. 2017, Yamaguchi and Shinmura, 2004). The electrolyte was made by dissolving the required amount of NaNo3 in water.

The workpiece was clamped in the chuck, and the magnetic pole position was adjusted to achieve the desired working gap. Mechanical mixing of iron and SiC particles in 75:25

weight proportions was used to create the MAPs, which were then filled in the working gap. By adjusting the electrode position, the electrode gap was ascertained. To provide relative motion between the workpiece and the MAPs, the workpiece was rotated at the desired speed using the CNC dashboard. The electrolyte supply was started at the desired flow rate at the same time. The direct current power supply was turned on, causing current in the electrode gap. Finishing was done continuously for 10 minutes. Table 1 displays the various experimental parameter conditions used in the experiment.

Table 1. Experimental parametric conditions

Name of Parameters	*Conditions*
Workpiece	SS420 cylinder with 10 mm diameter and 100 mm length
Ferromagnetic particle type	Fe grit (mesh size 150µm)
Abrasives type	Silicon Carbide (1200 mesh no.)
Ferromagnetic and abrasives particles mixing ratio (Fe : SiC)	75:25
Working Gap (mm)	1, 2, 3, 4, 5
Electrolytic current (A)	1, 2, 3, 4, 5
Workpiece rotational speed (rpm)	200, 400, 600, 800, 1000
EFR (Litres/Hour)	5, 10, 15, 20, 25
Electrode Gap (EG) (mm)	1, 2, 3,4, 5

After finishing, the SR (Ra) of the cylindrical workpiece was measured at three different places on the finished diameter with equal angular spacing. The average of three Ra was considered the final Ra. SURFTEST SJ-410 was used to measure SR. After finishing, the SR (Ra) of the cylindrical workpiece was measured at three different places on the finished diameter with equal angular spacing.

The enhanced process performance of ECMAF as compared to MAF and ECD when applied independently were calculated by conducting experiments at no electrolytic current and no magnetic flux density respectively.

3. Results and Discussion

In this section, the performance of the modified ECMAF using the OPAT approach during the finishing of SS420 is analyzed scientifically, i.e., SR and MR are plotted on the 2D line graphs with double Y regarding the variation of input process parameters and discuss the variation trends.

3.1 Influence of working gap on SR and MR

The effect of the working gap on the MR and SR is exhibited in Fig. 5. As the working gap increase from 1 mm to 2 mm, there is a decrease in SR and an increase in MR. This is because MAPs get appropriate space for the movement resulting in more abrasives participating in finishing and a reduction in the number of peaks. The SR and MR obtained at 2 mm of working gap are 0.16 m Ra and 48 mg, respectively. Beyond 2 mm, a significant decrease in magnetic flux density in the working gap weakens the FMAB and reduces the cutting forces required for finishing. As a result, only smaller peaks are truncated, resulting in a lower MR while an increase in SR.

Fig. 6 presents the effect of NaNo3 Concentration on the SR and MR. As depicted, increasing the concentration of NaNo3 from 5% to 20%, SR decreases, and MR increases. This is due to the availability of more ions increases the current flow in the electrode gap, produces thick passive film which is subsequently removed by magnetic abrasion. It further promotes abrasion-passivation synergism and improve the finishing performance. After 20%, further increase of NaNo3 concentration results in thick formation of passive film which may not be removed by FMAB during MAF. As a result, no new work surface is provided for further ECD, reducing synergy and, ultimately, finishing performance.

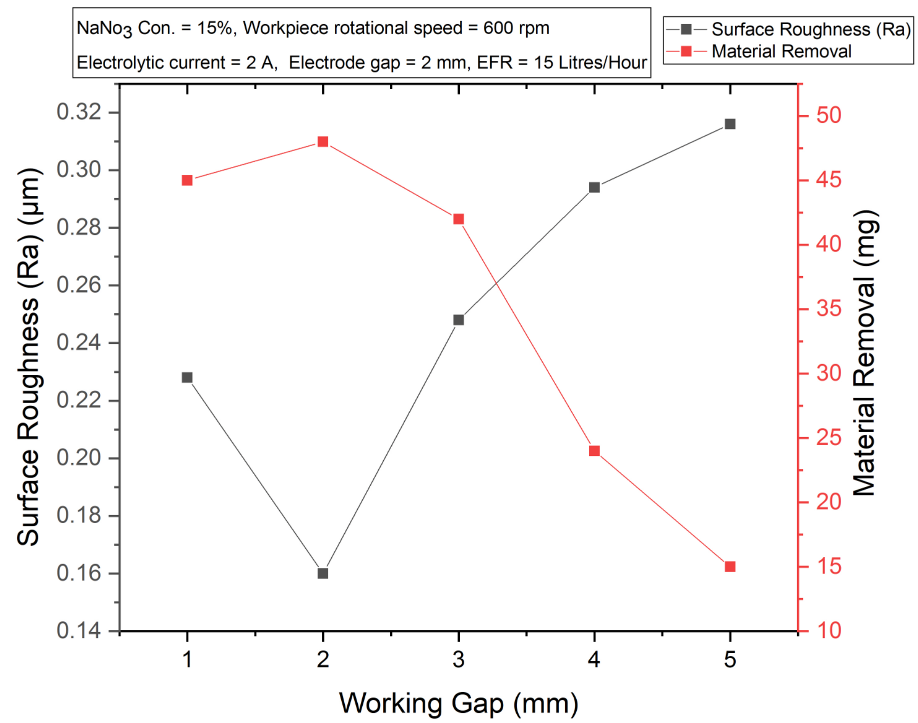

Fig.5. Influence of working gap on SR and MR

3.2 Influence of the NaNo3 concentration on SR and MR

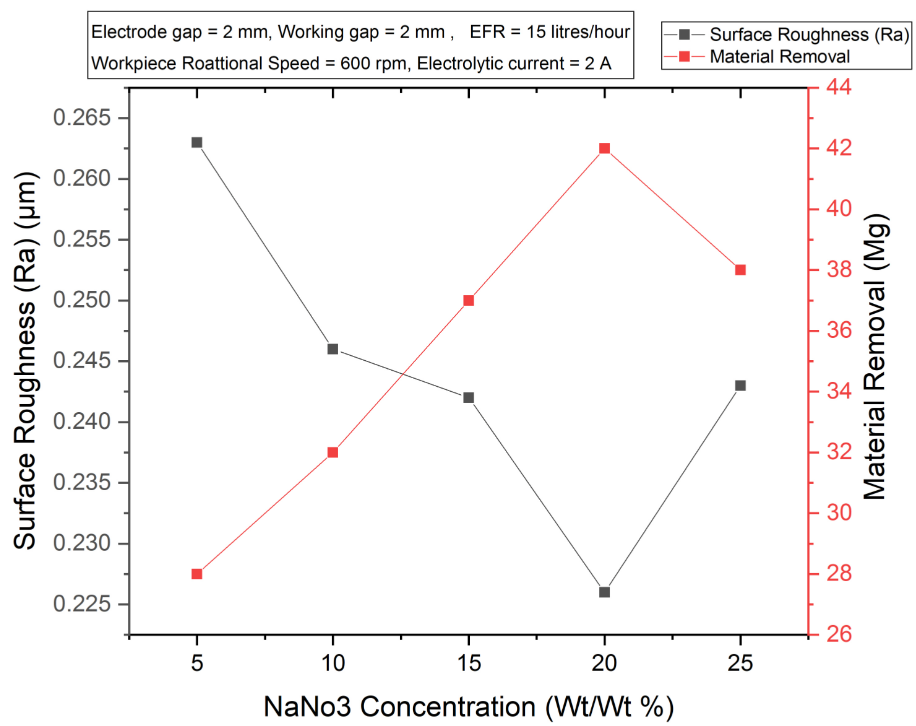

Fig.6. Influence of NaNo3 Concentration on SR and MR

3.3 Influence of the workpiece rotational speed on SR and MR

The effect of the workpiece rotational speed on the SR and MR is displayed in Fig. 7. As the workpiece rotational speed rise from 200 rpm to 600 rpm, SR decreases, and MR increases. This is because at specific parameter setting abrasive scratches peaks of surface irregularities over the periphery many number of times in specific machining time as speed increases. Hence, peaks are truncated several times, and the frequency of new surface exposure for passivation increases which improves finishing performance of the process. This is because FMAB will be disturbed, and abrasives may not reach the deep valley and finish. In addition, there may be very little time available for ECD at high speed. As a result, MR decreases while SR increases.

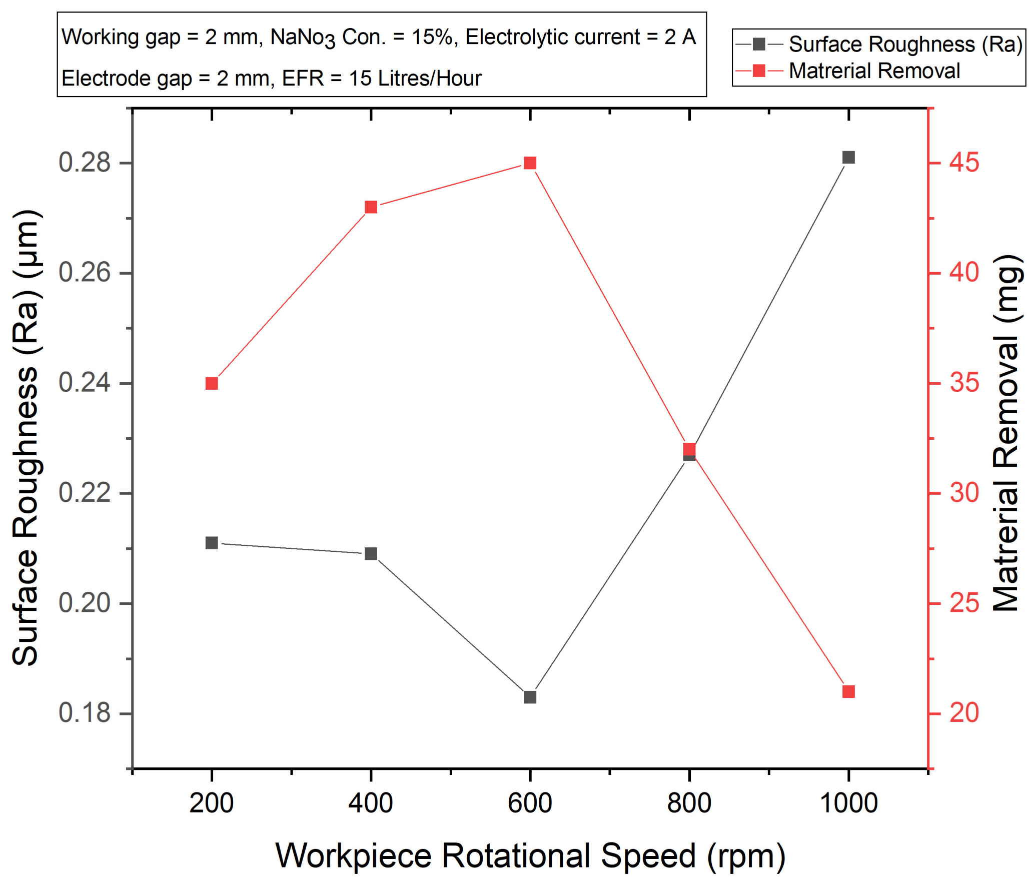

Fig.7. Influence of workpiece rotational speed on SR and MR

3.4 Influence of the EFR on SR and MR

Fig. 8 elucidates the EFR effect on the SR and MR. As the EFR rises from 5 to 20 litres per hour, SR decreases and MR rises. With increase in EFR, the electrolytic channel in electrode gap becomes continuous without any interruption which favours ECD. Appropriate MAF and electrolytic parameters enhances passivation-abrasion synergism. After 20 Litres/Hour of EFR, a large amount of electrolyte may flow in the electrode gap, providing a large amount of ions for ionisation and enhancing the ECD. MAF may not be able to completely eliminate this thick passive layer. As a result, no completely newer surface can be provided for future ECD. The synergy between the two processes is reduced as a result. As a result, SR rises while MR falls, lowering process performance.

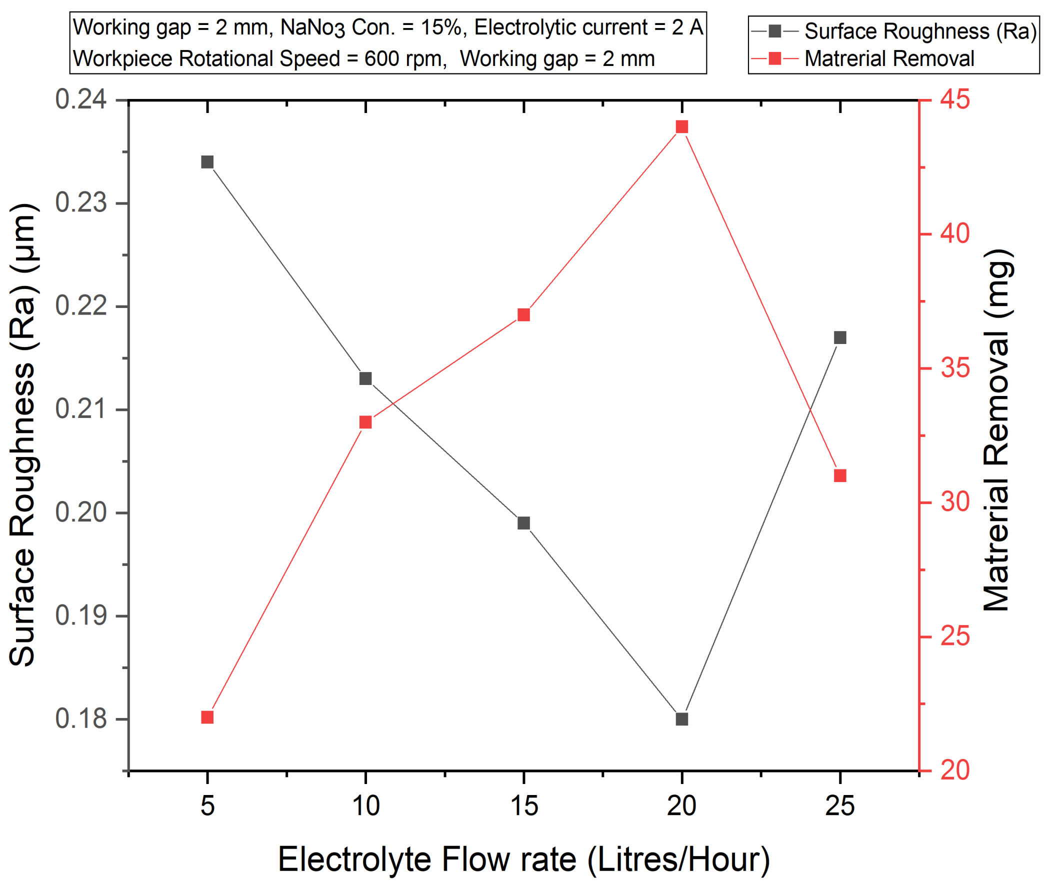

Fig.8. Influence of EFR on SR and MR.

3.5 Effect of the electrolytic current on SR and MR

Fig. 9 reveals the effect of the electrolytic current on the responses, SR and MR. With the rise in the electrolytic current from 1 A, the SR decreases, and MR increases. As the electrolytic current increases, the electrolysis rate increases, this produces a thicker passive film which removed by the abrasion. Hence abrasion-passivation synergism improves the performance of the process. After the 4A of electrolytic current, SR increases and MR decrease. A high current level in the electrode gap produces a thick, soft film that the abrasion cannot entirely detach. This minimizes the synergy of abrasion-passivation and finishing performance of the process. The lowest SR of 0.141 µm by removal of 46 mg material can be achieved at 4A of the electrolytic current and the SEM images of this workpiece before and after finishing are shown in Fig. 10. The surface of the finished workpiece is perfect and completely smooth. It is amply shown that the finished workpiece's surface finishing has significantly improved; confirming that the developed modified ECMAF successfully eliminates the workpiece's peaks.

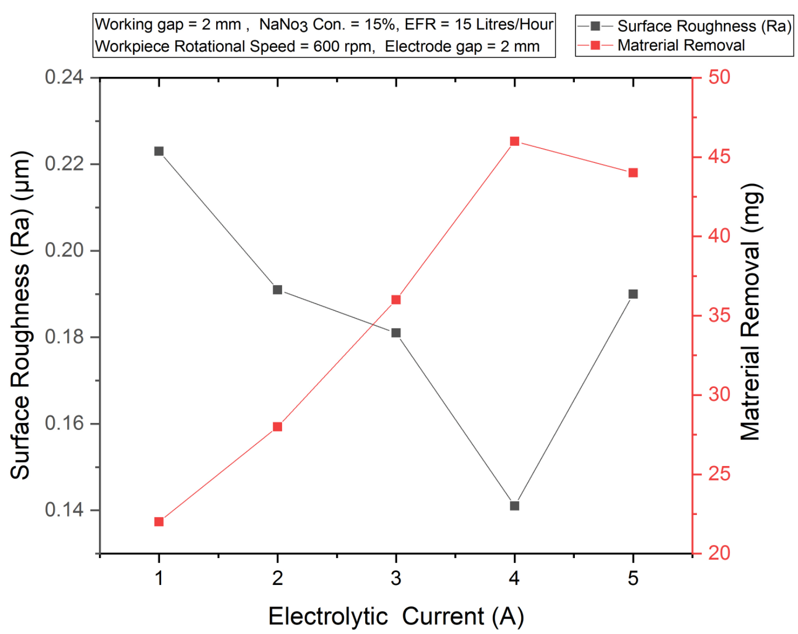

Fig.9. Influence of Electrolytic current on SR and MR

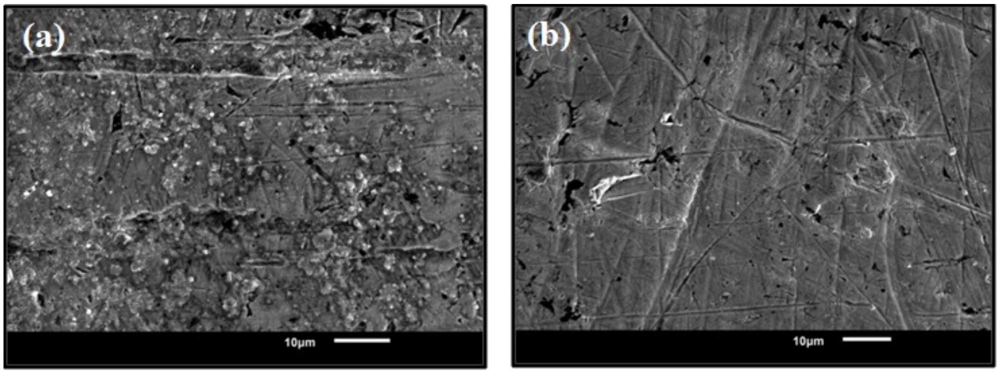

Fig.10. SS420 workpiece SEM images (a) before finishing (b) after finishing

3.6 Influence of the electrode gap on SR and MR

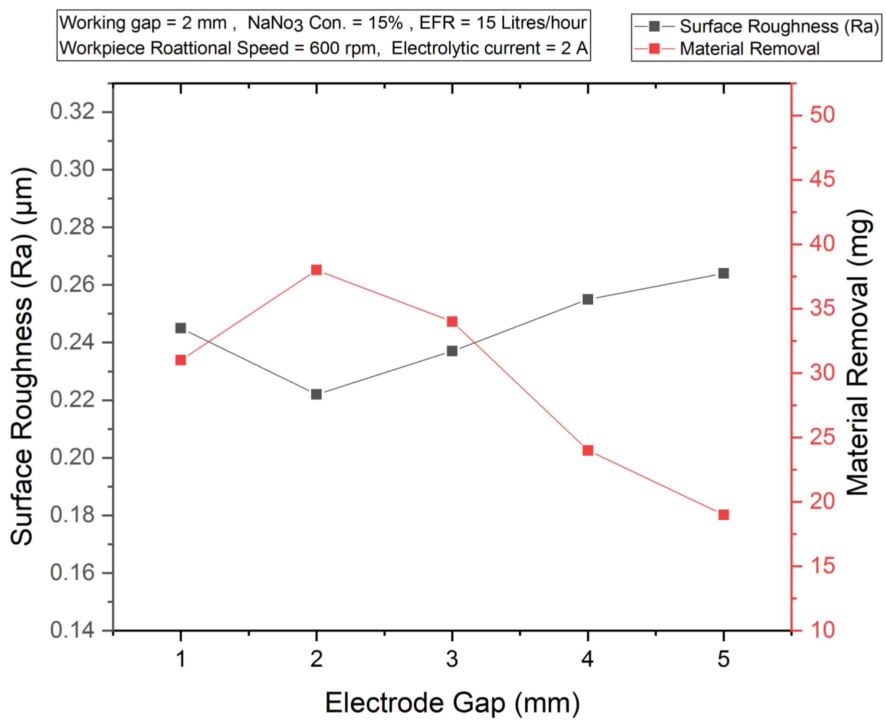

Fig.11. Effect of electrode gap on SR and MR

Fig. 11 demonstrates the effect of the electrode gap on the SR and MR. When the electrode spacing is initially raised from 1 mm, MR increases while SR decreases. The velocity of the electrolyte decreases as the electrode gap widens. As a result, the electrolyte has ample time for electrolysis. This results in a thick passive layer that the abrasion completely removes, enhancing the synergy. Beyond the 2 mm electrode gap, the electrolyte's velocity is significantly reduced, and some of the electrolyte falls into the reservoir without reaching the workpiece. This reduces ECD and creates a thin soft film. As a result, subsequent MAF do not receive enough thick passive film to be removed by abrasion. Due to this, the synergy between abrasion and passivation is reduced when a little amount of electrolyte is used for passivation. At 2 mm of electrode gap, the best performance, 0.222 μm of Ra and 38 mg of MR, is obtained.

3.7 Feasibility of the modified ECMAF process

Fig. 12 shows the MR of the modified ECMAF for various electrolytic currents. Due to no parameter modification during MAF, MR_{MAF} is constant. MR_{ECD} increases as the electrolytic current increases up to 4A current during ECD. This can be the result of a higher current density dissolving more peaks. After the 4A, MR_{ECD} decreases. This might be because the thick passive layer that forms on the surface as a result of high current prevents further passivation. During the modified ECMAF, the MR_{EXTRA} is also increased up to 4A current. That may be because the MAF completely removes the passive film created by the ECD, exposing a new surface to the ECD for further passivation. Hence, abrasion- passivation synergism improves, which increases the MR_{EXTRA}. MR_{EXTRA}. Beyond 4A, the MR_{EXTRA} declines because the abrasion does not completely remove the thick passive film that has developed on the surface, reducing the synergy of abrasion-passivation. The MR obtained during the modified ECMAF process is 73.91 percent higher at 4A electrolytic current than the total MR of the individual constituent processes. The SR is shown in Fig. 13 during the MAF, ECD, and modified ECMAF at various electrolytic currents. At 4A electrolytic current, modified ECMAF reduces SR (Ra) 73.43% more than ECD. Thus, it becomes clear that, at all electrolytic currents, modified ECMAF gives better surface finishing than individual constituent processes. This is due to the synergism of abrasion- passivation.

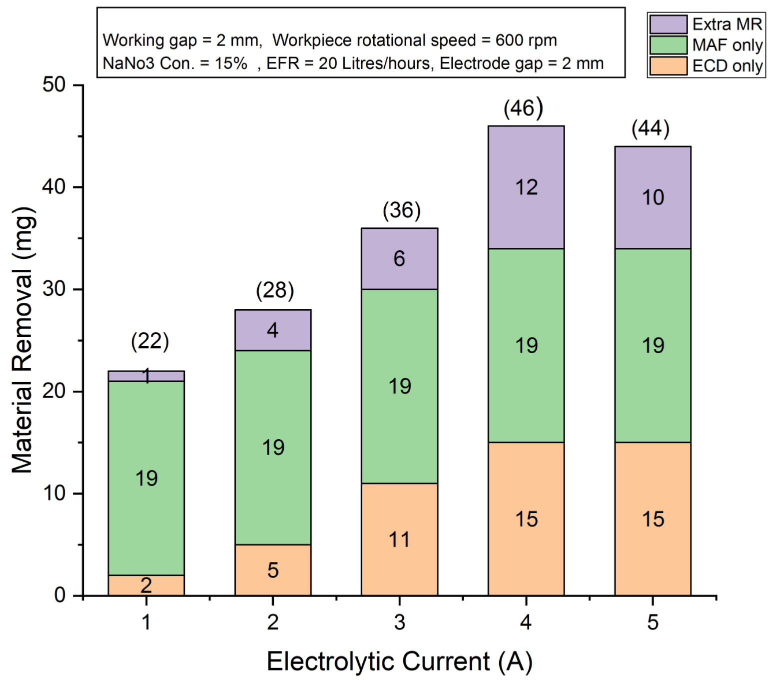

Fig.12. MR_{MAF}, MR_{ECD}, and MR_{EXTRA} representations at different electrolytic currents

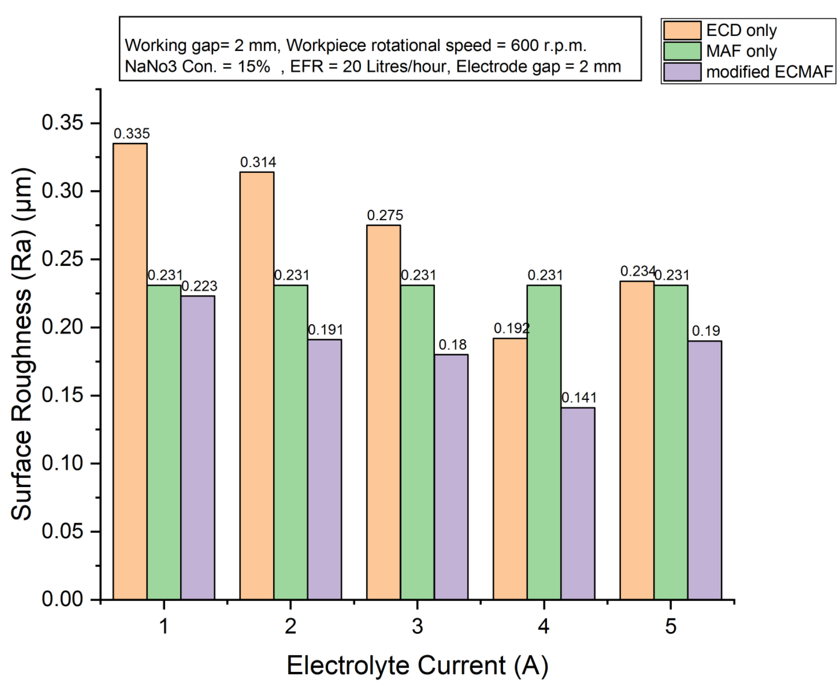

Fig.13. SR representations in MAF, ECD, and modified ECMAF at various electrolytic currents

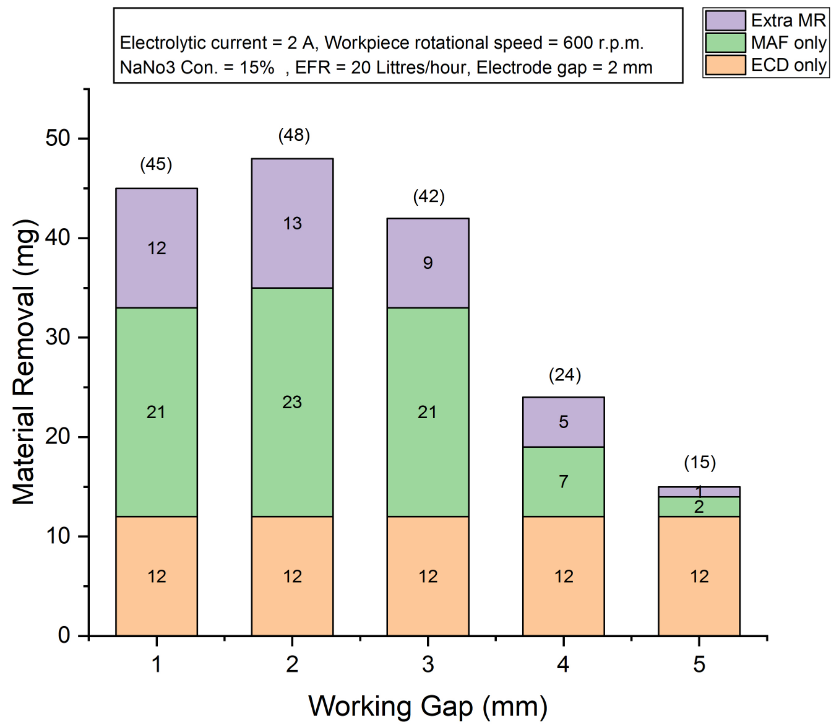

Fig.14. MR_{MAF}, MR_{ECD}, and MR_{EXTRA} representation at various working gaps

The MR_{MAF}, MR_{ECD}, and MR_{EXTRA} are shown in Fig. 14 at various working gaps. As the working gap widens from 1 mm to 2 mm, MR_{MAF} rises as abrasives are given adequate room to carry out finishing. After 2 mm of working gap, MR declines because a wider working gap causes more magnetic flux to leak out and weakens FMAB. Since ECD is conducted with constant parameters, the MR_{ECD} is constant. The MR during the modified ECMAF is shown at each working gap's top of the bar. The MR_{EXTRA} rises when the working gap rises from 1 mm to 2 mm. It may be because there is enough room for abrasives to move around and take part in finishing, and completely passive film removal by abrasion enhances abrasion-assisted passivation and produces a synergistic effect. Beyond a working gap of 2 mm, magnetic flux leakage may intensify, resulting in weaker FMAB and fewer MR, minimising abrasion-assisted passivation, and subsequently reducing MR_{EXTRA}. At 2 mm of a working gap during the modified ECMAF, MR is seen to have increased by 72.91 percent when compared to the total of MR during the MAF and ECD. The SR is shown on a clustered column chart in Fig. 15 during the MAF, ECD, and modified ECMAF at various working gaps. At a working gap of 2 mm, the modified ECMAF reduced Ra by 61.3 % more than the MAF. In comparison to the other two processes, the modified ECMAF is more efficient and produces preferred SR results.

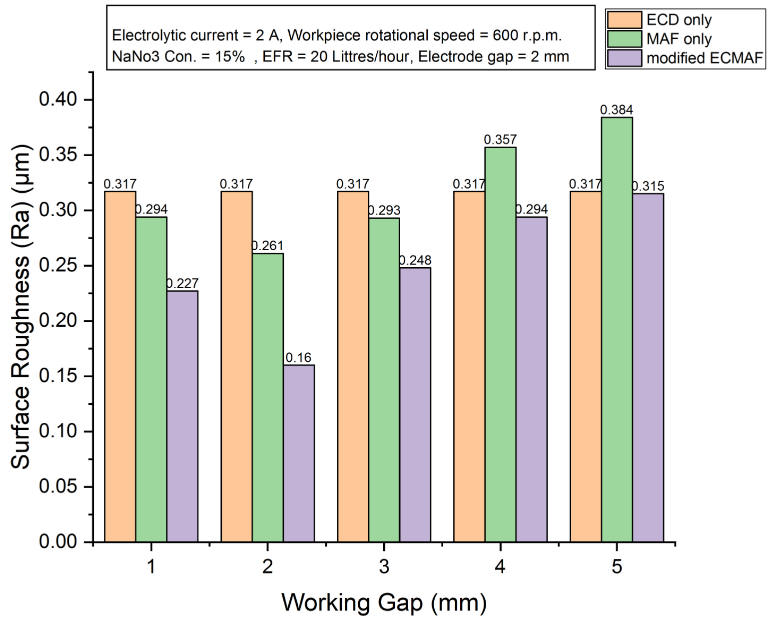

Fig.15. SR representations in MAF, ECD, and modified ECMAF at various working gaps

3.8 ECMAF: magnetic verses non-magnetic material

The finishing performance of the modified ECMAF is investigated while finishing nonmagnetic SS 304 and magnetic SS 420 materials at various working gap and electrolyte current. Fig. 16 depicts the MR at different working gaps while finishing SS 420 and SS 304 on modified ECMAF. For all working gaps, the MR of the SS 420 workpiece is found to be greater than the MR of the SS 304 workpiece. This is due to the fact that when finishing SS 420, a high magnetic flux density in the working gap performs magnetic abrasion more effectively than an SS 304 under all working gap conditions. In particular, the MR of SS 420 at 2 mm working gap is 11.63% higher than that of SS 304. Fig. 17 depicts the SR at different working gaps while finishing SS 420 and SS 304 on modified ECMAF. The SR obtained while finishing SS 420 is lower than that obtained while finishing SS 304. Because of the high magnetic flux density in the working gap, this produces a high cutting force and can reduce larger peaks. When finishing SS 420, modified ECMAF improves the SR by 13.13 percent more than SS 304 at 2 mm of working gap.

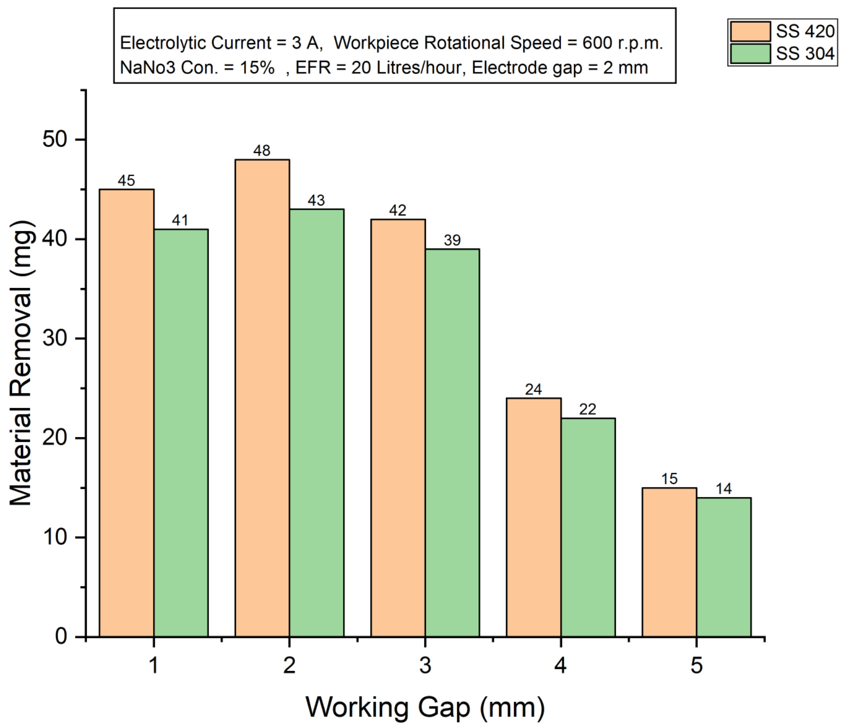

Fig.16. MR at various working gaps during the finishing of SS 420 and SS 304 on modified ECMAF

Fig. 18 depicts MR during SS 420 and SS 304 workpiece finishing at various electrolytic currents. When finishing SS 420, the MR is found to be greater than when finishing SS 304. In comparison to SS 304, this provides more abrasion force and effectively removes passive film due to the high magnetic density in the working gap. At 4A of electrolytic current, the MR of SS 420 is 15% higher than that of SS 304. Fig. 19 shows the SR during the finishing of SS 420 and SS 304 workpieces at different electrolytic currents. When compared to SS 304, the SR of SS 420 is lower during the finishing process. This is because higher magnetic flux density provides more cutting force and removes large peaks. At 4A of electrolytic current, the SR improves by 17% more than SS 304.

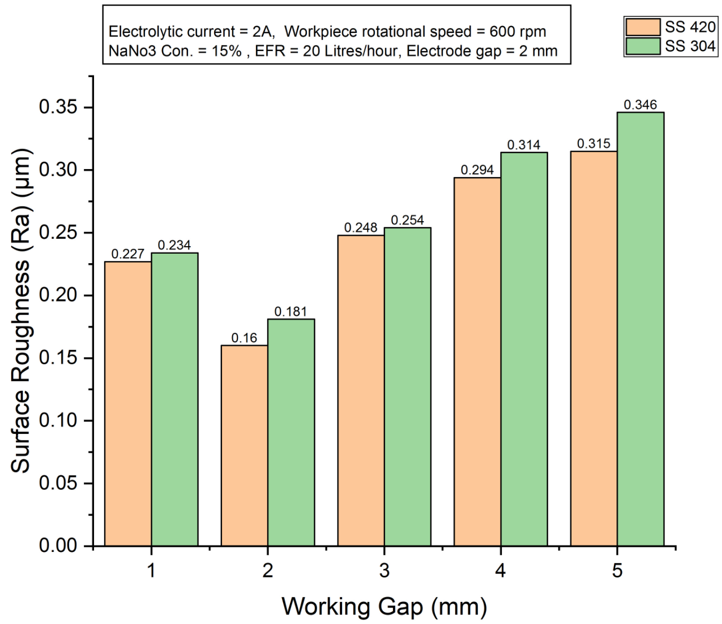

Fig.17. SR at various working gaps during the finishing of SS 420 and SS 304 on modified ECMAF

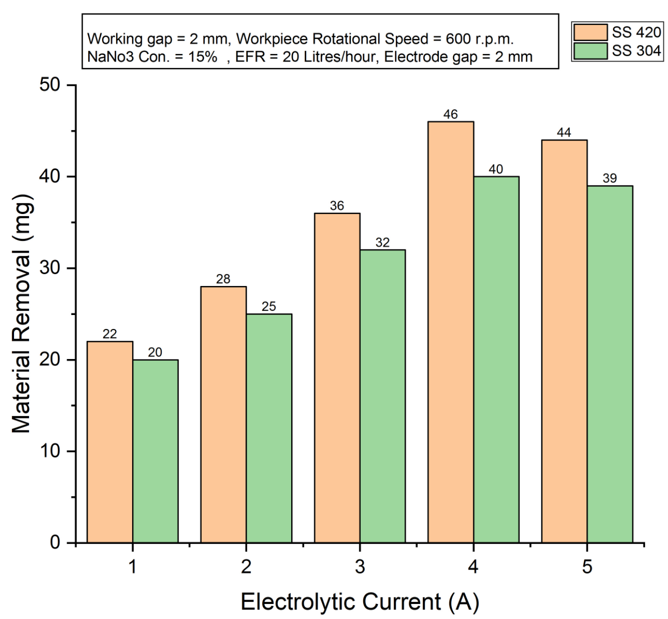

Fig.18. MR at various electrolytic current during the finishing of SS 420 and SS 304 on modified ECMAF

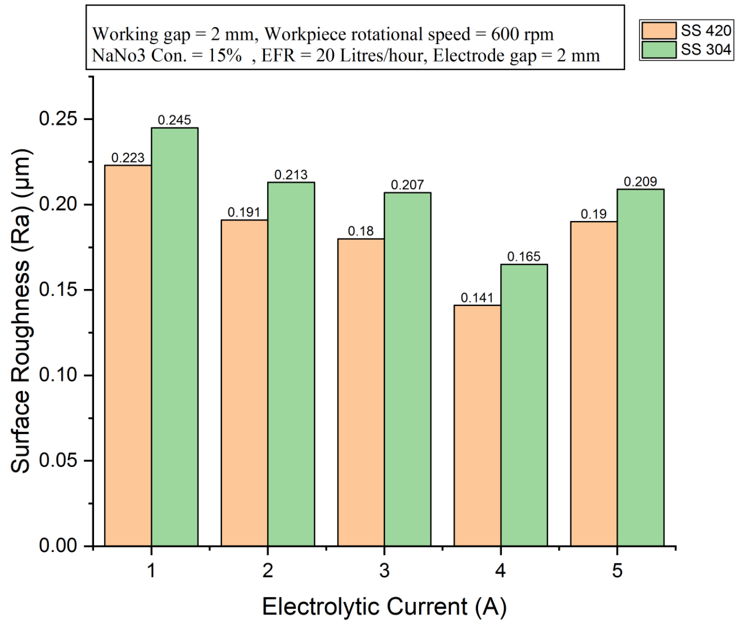

Fig.19. SR at various electrolytic current during the finishing of SS 420 and SS 304 on modified ECMAF.

4. Conclusion

The modified ECMAF has experimented with a magnetic SS420 workpiece. Parametric studies to identify the impact of a work gap, $NaNo_3$ concentration, electrolytic current, workpiece rotational speed, EFR, and electrode gap on finishing performance was carried out by following the OPAT approach. The feasibility was examined, and the performance of the process for magnetic and non-magnetic steel for SR and MR was compared. The derived critical points from the present study are tabulated below.

(1) Modified ECMAF finish the magnetic material SS420 effectively and at 4A electrolytic current, mirror-like surface roughness of 0.141 µm Ra was achieved, and 48 mg MR was attained at the working gap of 2 mm.

(2) The ECMAF's feasibility has been investigated, and it was found that the modified ECMAF reduces SR by 73.43 percent more and produces MR that is 73.91 percent more than the total of the constituent processes.

(3) SR lowers 17% more and MR rises 15% more when finishing magnetic steel SS 420 compared to finishing non-magnetic steel SS 304.

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