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# Improvement of Surface Roughness Quality for Stainless Steel 420 Plate Using Magnetic Abrasive Finishing Method

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## Abstract

An experimental study was carried out to improve the surface roughness quality of the stainless steel 420 using magnetic abrasive finishing method (MAF). Four independent operation parameters were studied (working gap, coil current, feed rate, and table stroke), and their effects on the MAF process were introduced. A rotating coil electromagnet was designed and implemented to use with plane surfaces. The magnetic abrasive powder used was formed from 33%Fe and 67% Quartz of (250µm mesh size). The lubricant type SAE 20W was used as a binder for the powder contents. Taguchi method was used for designing the experiments and the optimal values of the selected parameters were found. An empirical equation representing the relation between surface roughness with operation parameters have been achieved.

**Keyword:** *Magnetic abrasive finishing, MAF, abrasive powder, surface roughness, inductor, taguchi method, orthogonal arrays, electromagnetic poles.*

## 1. Introduction

Magnetic abrasive finishing (MAF) can be classified as nontraditional super finishing method for finishing surfaces with different shapes and working materials like flat plates, shafts, bearings parts, screws, tubes and many other mechanical parts that need a good surface finishing properties. MAF is effective in polishing, cleaning, deburring and burnishing metal parts. One of the main advantages of MAF operation as compared with traditional fine finishing operations like grinding, honing or lapping is the minimizing of the possibility of microcracks on the surface of the workpiece because the cutting force is primarily controlled by the magnetic field and the finishing tool is a flexible magnetic brush forming from magnetic abrasive powder, while the other traditional finishing processes employ a rigid tool that subjects the workpiece to substantial normal stresses which may cause microcracks resulting in reduced strength and reliability of the machined part [1].

Following recent technological developments, stainless steel materials with characteristics of anti-oxidizing, anticorrosive, and shiny surface have been applied in electronic, biochemical and medical instrumentation equipments. The surface of stainless-steel parts must be extremely smooth to prevent pollution. Optimally, the surface finish can reach a level where it looks like a mirror. Stainless steel is a soft, tough, and difficult finishing material. Thin-plate stainless steel that uses traditional processes is not easy to achieve a good surface finish. Manual finishing was usually applied to achieve a surface finish that looks like a mirror. However, it is very time consuming and inefficient to achieve a good surface finish using manual finishing techniques for stainless container steel surfaces. To resolve these problems, magnetic abrasive finishing (MAF) was recently created. MAF involves the use of a permanent magnet or an electronic magnet to generate a magnetic field [2].

In MAF, the workpiece is kept between the two poles of a magnet. The working gap between the workpiece and the magnet is filled with magnetic abrasive particles. The magnetic abrasive particles join each other along the lines of magnetic force and form a magnetic abrasive flexible brush (MAFB) between the workpiece and the magnetic pole (Fig. 1). This brush behaves like a multi-point cutting tool for the finishing operation. When the magnetic N-pole is rotating, the MAFB also rotates like a flexible grinding wheel and finishing is done according to the forces acting on the abrasive particles.

The method was originally introduced in the Soviet Union, with further fundamental research in various countries [3]. Recently many researchers concerned with developing this method and many publications were introduced in this field.

A theoretical investigation of the MAF process was introduced by Jayswal et al. [1]. A finite element model of the process is developed to evaluate the distribution of magnetic forces on the workpiece surface.

A permanent magnetic finishing mechanism was used by Ching et al. [2]. Their experimental data was collected using the Taguchi experimental design. The optimal parametric conditions for processing stainless SUS304 material were applied in a two-stage process comprised of rough finishing that involved MAF followed by a precise finishing of the surface.

Wang and Hu [3] described the process principle and finishing characteristics of unbounded magnetic abrasive within internal tubing finishing. They also deal with the design and fabrication of MAF setup for finishing three kinds of materials tubing, such as Ly12 aluminum alloy, 316L stainless steel and H62 brass.

Geeng et al. [4] Described in their study, the process principle and the finishing characteristics of unbounded magnetic abrasive within cylindrical magnetic abrasive finishing. They investigated the finishing characteristics on surface roughness and material removal as well as their mechanisms.

Mori et al. [5] examined the magnetic field, acting forces and provides a fundamental understanding of the process mechanism. A planar type process for a non-magnetic material, stainless steel, was introduced.

Maiboroda and Khomenko [6] investigated how the frictional force between magnetic-abrasive powders and a Ti alloy surface varies during magnetic-abrasive machining in relation to the technological parameters. They studied experimentally the effects of five types of powders with different grain sizes.

Singh et al. [7] applied Taguchi design of experiments to find out important parameters influencing the surface quality generated using MAF process. The parameters used are: (i) voltage (DC) applied to the electromagnet, (ii) working gap, (iii) rotational speed of the magnet, and (iv) abrasive size (mesh number).

Baron et al. [8] analyzed the effectiveness of using Magnetic Abrasive Finishing (MAF) to remove burrs on drilled holes located on planes.

By using X-ray diffraction analysis and electron-probe microanalysis, Stepanova et al. [9] have studied TiC coatings obtained by chemical vapor deposition, where the base and subsequently the coating have undergone magnetic abrasive finishing

Yascheritsin et al. [10] introduced a comparative data of quality characteristics of parts from steel 45 and 12X2H4A after grinding, honing and magnetic abrasive machining. They found that the MAF forms optimum physical-mechanical properties of surface layer which are more relative to operation.

Gogaev et al. [11] clarified by using electron microscopy, magnetic and friction methods, that a mixture of magnetic γ-$Fe2O3$ and abrasive powders, properly processed, can be used as a material for magneto abrasive machining and polishing of variously shaped components.

Dhirendra et al. [12] reported the experimental findings about the forces acting during MAF and provides correlation between the surface finish and the forces.

By using the developed electromagnetic inductor for deburring micro burr, Ko et al [13] analyzed a more detail characteristics of the performance. They were carried out experiments to verify the influence of each conditions: volume of powder, height of gap, rotational frequency of the inductor and feed velocity.

The objective of this paper is to experimentally prove the validity of the magnetic abrasive method for finishing stainless steel flat surfaces, studying the effect of changing four independent operating parameters on the process (inductor current, working gap, feed rate and number of working stroke), and then to obtain an empirical equation representing the relation of these parameters with the change in surface roughness.

## 2. Experimental Considerations

The schematic of the apparatus used to implement the experiments is shown in Fig. (1). The design of the apparatus is based on the models used in references [7] and [8] with some required modifications. The primary manufactured model includes two electromagnetic poles; the inner pole (north) and the outer pole (south), this makes the powder to form from the inner pole towards the outer pole. This design is very efficient in deburring specially after drilling process. To use this model in finishing plane surfaces, the outer pole was removed leading to a single pole (the inner North Pole). In this case the south pole will be the ferromagnetic workpiece making the powder to arrange from the inner pole towards the workpiece as shown in Fig. (2). The whole device is mounted on a vertical milling machine (Fig. (3)).

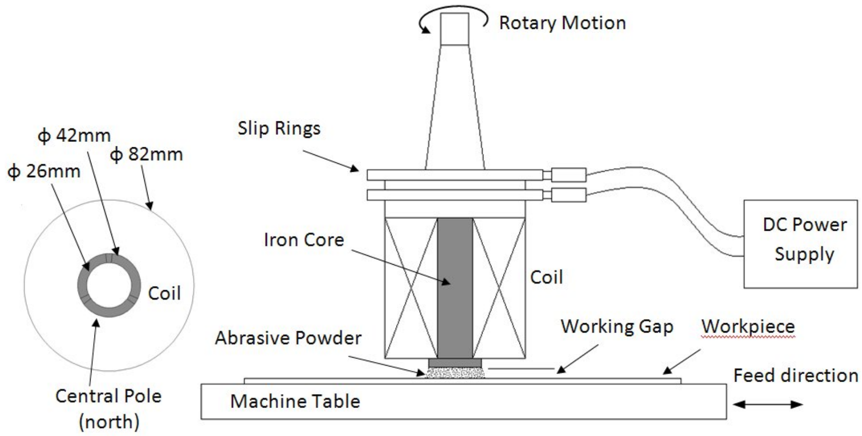


**Fig. 1. Schematic of the MAF Apparatus.**

**Fig.2. Magnetic Brush Formed between the Electromagnet Pole (North) and the Ferromagnetic Workpiece (South).**

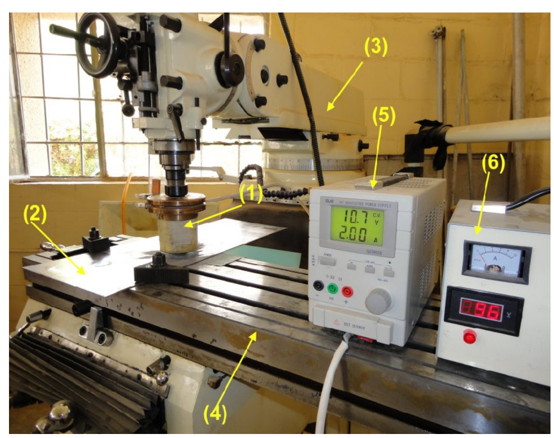


**Fig.3. Magnetic Abrasive Device (1) Electromagnetic Inductor, (2) Workpiece, (3) Vertical Milling Machine, (4) Moving Table, (5) Dc Power Supply, (6) Table Speed Control.**

The mechanism of MAF requires filling the working gap between the electromagnetic pole and the workpiece with the magnetic abrasive powder. The end face of the magnetic pole absorbs the powder and forms a closed-loop magnetic field with the ferromagnetic workpiece. The magnetic abrasives are generated in a non-uniformly magnetic field in which the abrasives will join each other and follow the direction of the magnetic force to form a flexible magnetic brush. The magnetic force lines generated power to apply pressure from the magnetic abrasives to the workpiece, and the magnetic brush became a tool for finishing the workpiece. Moreover, the magnetic abrasives in the magnetic brush stick to the workpiece. When the magnetic pole rotates with moving the workpiece relatively, the frictional force generated from MAF causes the abrasives to finish the particles of the surface until it becomes smooth [2].

## 3. Design of Experiments

In the present experiment, four independent parameters, each has three different levels were selected which are: (1) working gap, (2) current supplied to the coil of the magnet, (3) workpiece feed rate and (4) working stroke. The ranges of operating parameters are listed in Table 1.

**Table 1,**
**Parameters and Their Levels.**

| Parameter | Unit | Levels |
|---|---|---|
| Working gap (P1) | mm | 1.5 - 2.0 - 2.5 |
| Coil current (P2) | Amp. | 2.0 - 2.5 - 3.0 |
| Feed rate (P3) | cm/min | 3.0 - 5.0 - 7.0 |
| Table stroke (P4) | No. | 1 - 2 - 3 |

A full factorial experiment would require $3^4$ = 81 experiments. Taguchi method was used to design the experiment with $L_9(3^4)$ orthogonal array (9 tests, 4 variables, 3 levels), (Table 2) which leads to reduce the high required number of experiments to 9 effective experiments [2, 7].

The magnetic abrasive powder used is formed from 33%Fe and 67% Quartz of (250 µm mesh size) bounded together by wetting the powder using SAE 20W lubricant. Addition of lubricant increases the adhesive force between the iron particles and the quartz abrasives as well as between iron particles themselves. This increases the binding strength between the particles and hence strength of flexible magnetic abrasive brush [12]. The volume of the powder used is (6 $cm^3$) for each experiment and the lubricant added not to exceed 5% of the powder volume.

The workpiece plate material is a martensitic grade stainless steel type 420, which its properties are listed in Table 3.

The other design data are:
Spindle rotational speed = 475 rpm, number of windings for the magnet coil =1400 turn, wire size=19 AWG.

**Table 2,**
**Orthogonal Array $L_9(3^4)$.**

| Exp. | P1 | P2 | P3 | P4 |
|---|---|---|---|---|
| 1 | 1* | 1 | 1 | 1 |
| 2 | 1 | 2 | 2 | 2 |
| 3 | 1 | 3 | 3 | 3 |
| 4 | 2 | 1 | 2 | 3 |
| 5 | 2 | 2 | 3 | 1 |
| 6 | 2 | 3 | 1 | 2 |
| 7 | 3 | 1 | 3 | 2 |
| 8 | 3 | 2 | 1 | 3 |
| 9 | 3 | 3 | 2 | 1 |

* (1, 2 and 3) are the lower, intermediate, and higher values respectively.

**Table 3,**
**Properties of Stainless Steel Type 420.**

| Composition ranges (%) | | | | | | |
|---|---|---|---|---|---|---|
| Element | C | Mn | P | S | Si | Cr |
| min. | 0.15 | - | - | - | - | 12.0 |
| max. | - | 1.0 | 0.04 | 0.03 | 1.0 | 14.0 |

| Mechanical properties | | | |
|---|---|---|---|
| Ultimate strength (MPa) | Yield strength (MPa) | Elongation in 50.8mm (%) | Hardness Rockwell |
| 586 | 276 | 25 | 88 HRB |

| Physical properties | | | | |
|---|---|---|---|---|
| Density ($g/cm^3$) | Electrical Resistivity (µΩ-cm) | Specific Heat (0-100°C) (kJ/kg•K) | Thermal Conductivity (W/m•K) | Modulus of Elasticity (MPa) |
| 7.74 | 55 | 0.46 | 24.9 | $200\times10^3$ |

The output data measured is the change in surface roughness ($\Delta Ra$) between the arithmetic mean surface roughness ($Ra$) of the workpiece before and after MAF experiments. Surface roughness tester (SRT-6210) used to measure the values of $Ra$ at three different places at same line in the workpiece after MAF taking the average value and then subtract from the average value of $Ra$ before MAF which is obtained from 27 readings of $Ra$ at different places of the workpiece ( the measured average value is 0.316 µm). Fig. (4) shows the value of $Ra$ obtained after finishing at one place on the workpiece (0.127 µm).

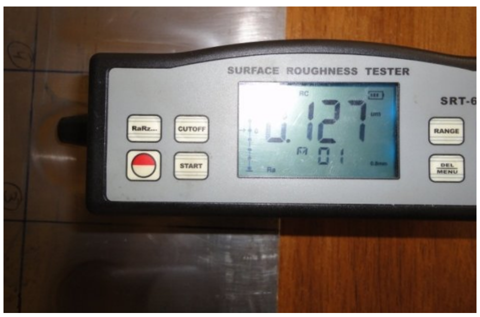


**Fig.4. Measuring the Value of *Ra* Using Surface Roughness Tester (SRT-6210).**

## 4. Results and Discussion

The experimental results obtained using magnetic abrasive finishing technique are summarized in Table 4. Nine experiments were conducted using Taguchi method for designing the experiments. The average $Ra$ results after MAF are listed in the table (the lower values are the best). These results show the decreasing in the magnitude of $Ra$ as compared with the primary value of the workpiece ($Ra$=0.316 µm), which indicates the validity of the MAF method in finishing the plane surfaces. The variance in the values of $Ra$ is due to the changing in the operation conditions in each experiment. The changes in surface roughness ($\Delta Ra$) are also listed in the table (the higher values are the best).

A statistical software (StatistiXL V1.8) has been used to analyze the experimental values of ($\Delta Ra$). Following linear regression model, the relationship between the values of $\Delta Ra$ with respect to the employed parameters has been found as following :

$$\Delta Ra = 0.157 - 0.072\, P_1 + 0.057\, P_2 - 0.001\, P_3 - 0.009\, P_4 \qquad \ldots(1)$$

The accepted absolute values of the percentage errors between the results obtained by the regression model and the experimental results (as listed in Table 5), show that the linear regression model (Eq. (1)) can be considered as a valid model for these experiments.

**Table 4,**
**Experiments Parameters and Obtaining Results.**

| Exp. | Working gap ($P_1$) (mm) | Coil current ($P_2$) (Amp.) | Feed rate ($P_3$) (cm/min) | Table stroke ($P_4$) | Average *Ra* (µm) | Average Δ*Ra* (µm) |
|---|---|---|---|---|---|---|
| 1 | 1.5 | 2.0 | 3.0 | 1 | 0.161 | 0.155 |
| 2 | 1.5 | 2.5 | 5.0 | 2 | 0.133 | 0.183 |
| 3 | 1.5 | 3.0 | 7.0 | 3 | 0.124 | 0.192 |
| 4 | 2.0 | 2.0 | 5.0 | 3 | 0.234 | 0.082 |
| 5 | 2.0 | 2.5 | 7.0 | 1 | 0.181 | 0.135 |
| 6 | 2.0 | 3.0 | 3.0 | 2 | 0.167 | 0.149 |
| 7 | 2.5 | 2.0 | 7.0 | 2 | 0.244 | 0.072 |
| 8 | 2.5 | 2.5 | 3.0 | 3 | 0.215 | 0.101 |
| 9 | 2.5 | 3.0 | 5.0 | 1 | 0.176 | 0.14 |

**Table 5,**
**Experimental and Regression Comparison.**

| Exp. | $\Delta Ra$ (μm) (Experiment) | $\Delta Ra$ (μm) (Regression) | Error (%) |
|---|---|---|---|
| 1 | 0.155 | 0.151 | 2.58 |
| 2 | 0.183 | 0.1685 | 7.92 |
| 3 | 0.192 | 0.186 | 3.12 |
| 4 | 0.082 | 0.095 | 15.85 |
| 5 | 0.135 | 0.1395 | 3.33 |
| 6 | 0.149 | 0.163 | 9.39 |
| 7 | 0.072 | 0.066 | 8.33 |
| 8 | 0.101 | 0.0895 | 11.38 |
| 9 | 0.14 | 0.134 | 4.28 |

**Table 6,**
**Percentage Contribution of Factors Influencing $\Delta Ra$.**

| Parameter | $\Delta Ra$ |
|---|---|
| Working gap ($P_1$) | 50.9 % |
| Coil current ($P_2$) | 39.9 % |
| Feed rate ($P_3$) | 3.2 % |
| Table stroke ($P_4$) | 7.0 % |
| Total | 100% |

Fig. (5), shows the relationship between the change in *Ra* (*$\Delta Ra$)* with electromagnet current for different values of working gap. The experimental and regression results are shown in this figure. The values of $\Delta Ra$ increase with increasing the supplied current for the introduced working gap but with increasing in the magnitudes for the lower values of working gap. This is because of the fact that increasing the supplied current will lead to generates more numbers of lines of magnetic force, and therefore higher flux density in the working gap [7]. The strength and the contact area of the magnetic brush with workpiece will increase leading to increase the cutting force leading to increasing the change in surface roughness values and obtaining smoother surface.

The relationships between the obtained experimental and regression values of $\Delta Ra$ and the working gap with different magnitude of supplied current are shown in Fig. (6). The same fact as mentioned in the previous article is proved and the values of $\Delta Ra$ increase with decreasing the working gap because of the higher values of the generated flux density leading to higher depth of micro-indentation between the flexible magnetic brush and the workpiece surface which will increase the magnitudes of $\Delta Ra$.

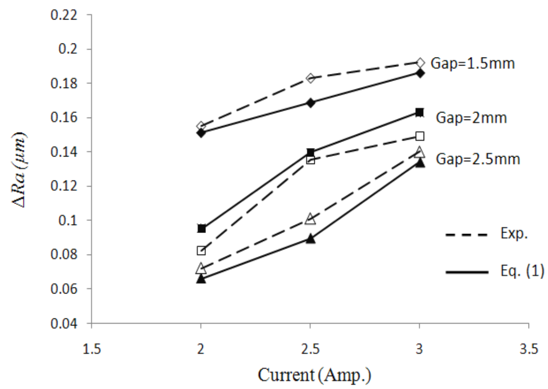


**Fig.5. Effect of Coil Current on $\Delta Ra$ for Different Values of Working Gap.**

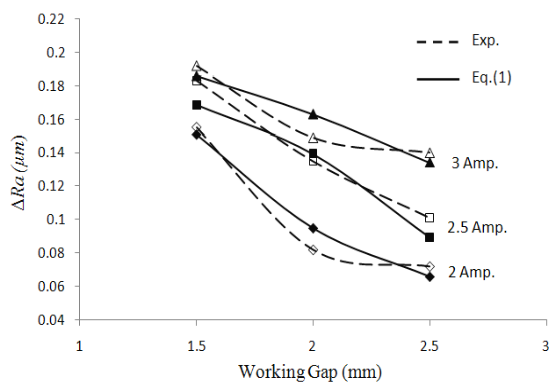


**Fig.6. Effect of Working Gap on $\Delta Ra$ for Different Values of Coil Current.**

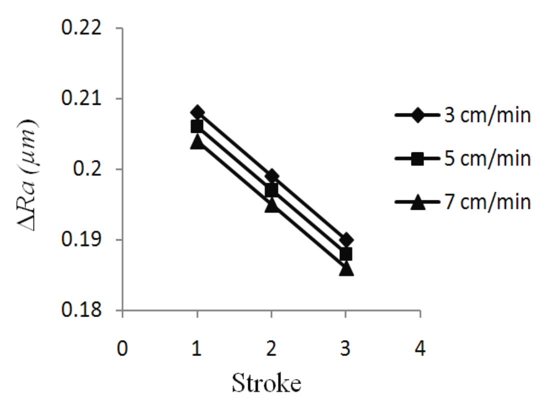


**Fig.7. Effect of Table Stroke on $\Delta Ra$ for Different Values of Feed Rates, ($P_1$=1.5mm, $P_2$=3 Amp.).**

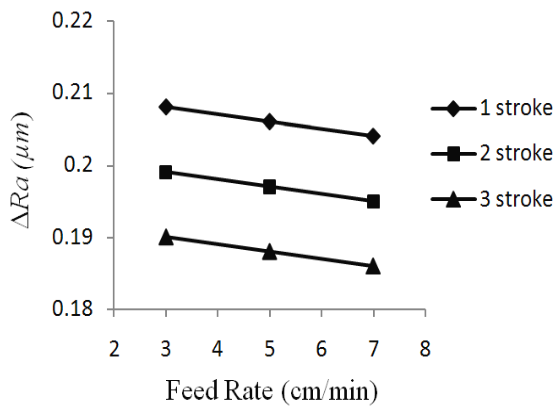


**Fig.8. Effect of Feed Rate on Δ*Ra* for Different Values Table Strokes of, ($P_1$=1.5mm, $P_2$=3 Amp.).**

Fig.(7), shows the change of the obtained regression values of Δ*Ra* and the values of the number of working stroke with different table feed rates. The trend of the curves is the same for different feed rates but the values of the Δ*Ra* is more for lower number of strokes. In single stroke the abrasive powder with specified mesh size remove the irregularities in the workpice surface and smoothing it, but when passing over the same smoothed surface in other stroke, the same powder with same mesh size could not make the improvement to the smoothed surface, in addition some abrasive particles lose their effectiveness and shape due to the mechanical contact with the workpiece surface making them to scratch the surface and then decreasing the surface smoothness. The slope of the change in Δ*Ra* values caused by changing table strokes is more than that caused by changing the values of feed rate as shown in Fig. (8). The increase of the feed rate decreases the values of Δ*Ra*. This makes the abrasive particles in the magnetic brush to pass over the workpice surface quickly without taking the enough time to make the smoothing process.

Figs. (9) and (10), show the effect of changing the values of working strokes and table feed rates respectively and the values of Δ*Ra* with different values of working gap and supplied current. The magnitude and the slope of the curves give an indication that the effect of feed rate on the change in *Ra* is less than the effect of the working stroke while the working gap and the electromagnet current are the dominant factors affecting the MAF process in finishing ferromagnetic flat plates within the ranges of the used parameters in present experiment.

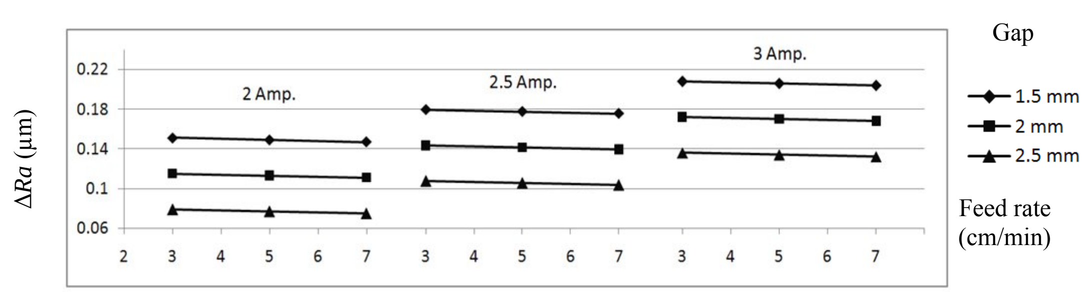


**Fig.9. Effect of Feed Rate on Δ*Ra* for Different Values of Current and Gaps ($P_4$=1).**

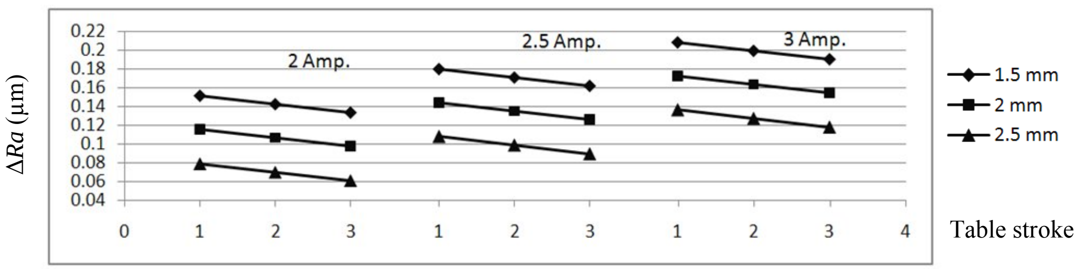


**Fig.10. Effect of Table Stroke on Δ*Ra* for Different Values of Current and Gaps ($P_3$=3).**

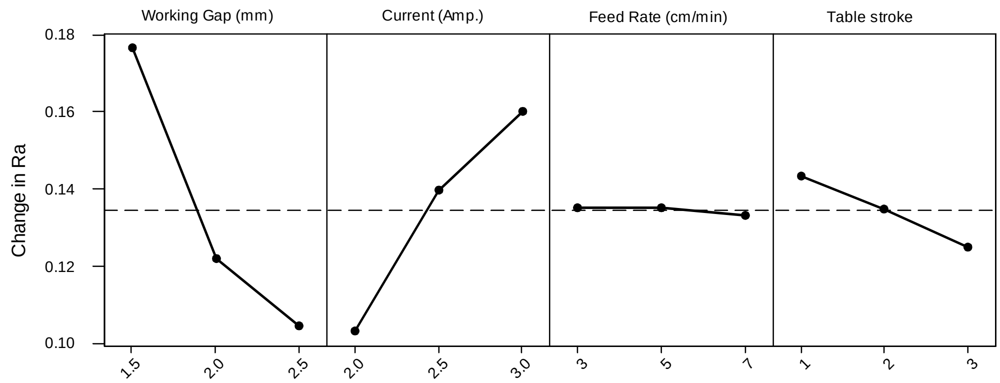


**Fig.11. Main Effects of Process Parameters on the Experimental Values of Δ*Ra*.**

The main effects of process parameters on the experimental values of Δ*Ra* were plotted in Fig. (11) using statistical software, by taking the mean value of the change in roughness at each level of the process parameters. The dotted line indicates the mean value of Δ*Ra* for the nine implemented experiments. These plotted curves show the mean behavior of Δ*Ra,* obtained when changing selected parameters and the importance level of each parameter on the process. The quality of the surface roughness increases with increasing the coil current, while it decreases when increasing each of the working gap, feed rate and table stroke.

According to Fig. (11), the level value of each parameter that give better surface quality (higher value of Δ*Ra* ), can be assumed as optimal quality level [11]. The optimal quality levels of each parameter are as follows: Working gap (1.5mm), coil current (3Amp.), feed rate (3 cm/min), and table stroke (1).

The parameters and their percent contributions influencing the change in *Ra* obtained from the statistical software were listed in Table 6.

It is concluded from the percentage contribution of the working gap and the coil current that they are the dominant parameters affecting the change in surface roughness, while the table stroke has small effect and smaller effect for the feed rate.

Fig. (12) show the graph of the workpiece surface after MAF experiment which show clearly the smoothness of the surface (*Ra* = 0.124 µm).

The validity of this method for finishing the ferromagnetic stainless steel 420 have been also proved by obtaining scanning microscopic views of workpieces before and after MAF (Fig. (13), a & b). These views show the texture generated by contacting the magnetic abrasive powder in specified operating conditions with the workpiece surface and the apparently smoothness occurs due to the application of the magnetic abrasive finishing process. The highly scratched surface before MAF was smoothed and the direction of the obtained texture after MAF was changed according to the direction and the rotation of electromagnetic pole. The optical microscopic views were conducted in Al- Khwarizmi College of Engineering – Manufacturing Engineering department.

**Fig.12. Workpiece after MAF Experiment (*Ra* =0.124 µm).**

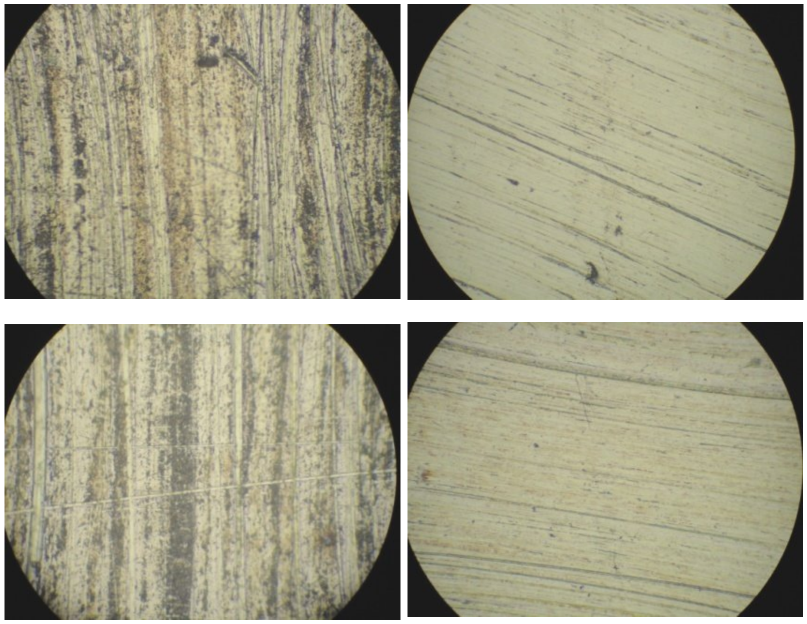


**Fig.13. Optical Microscopic Scanning Views (×1250) of the Workpieces of Experiment 2; (a) and Experiment 3, (b) Before and After MAF.**

## 5. Conclusions

Magnetic abrasive finishing method was implemented in this experimental study, for finishing and improving the quality of the ferromagnetic stainless steel 420 plate. It was found that changing the operation parameters will affect the quality of workpiece surface. The most significant parameter is the working gap followed by the supplied current. Working stroke and the feed rate found to have a small effect on the change in workpiece roughness. Linear Regression analysis gives an accepted rapprochement with the experimental data. The obtained data show that the values of $\Delta Ra$ increase with increasing the supplied current while it decreases with increasing the values of the working gap, stroke and the feed rate.

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# تحسين جودة نعومة السطح لصفائح الصلب نوع (٢٤٠) باستخدام طريقة الحث المغناطيسي

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**الخلاصة**

تم في هذا البحث اجراء دراسة عملية لتحسين جودة السطح من حيث الخشونة للصلب المقاوم نوع ٢٤٠ باستخدام طريقة الحث المغناطيسي وذلك بدراسة تاثير أربعة عوامل تشغيلية وهي: ١-الفراغ بين القطب المحث والمشغولة و٢-التيار و٣-سرعة التغذية و٤-أشواط التغذية. تم تصميم وتصنيع محاث كهرومغناطيسي ملف دوار للاستخدام في التجارب تم استخدام مسحوق تنعيم (٣٣% حديد و ٦٧ % كاوارتز) بنعومة (٢٥٠ µm) واضافة الزيت نوع SAE 20W كمادة رابطة بين مكونات المسحوق أستخدمت طريقة Taguchi لتصميم منظومة التجارب ومن ثم ايجاد القيم المثلى لعوامل التشغيل حيث تم ايجاد معادلة تجريبية تمثل العلاقة بين نسبة التغيير في خشونة السطح والعوامل التشغيلية المدروسة.