Optimizing the micro-hardness of a surface by magnetic abrasive finishing

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Abstract. In this work, the effect of different viscosities of an oil in magnetic abrasive finishing process (MAF) is analysed. The material specifically chosen for experimentation is Brass alloy (CuZn). The surface of the Brass alloy in this study was exposed to different tests during which key parameters were altered. In order to keep the objectives of this study aligned the list of parameters was limited to six. The six parameters were: Viscosity; Quantity of the powder (doze); Distance between pole and the work piece; Pole diameter; Pole rotational speed and Current. The choice of parameters was based on the Taguchi orthogonal array (OA), with three levels of variance for each parameter. To determine the signal to noise ratio (S/N) and to obtain the optimum condition of micro hardness, Hv, the statistical software (MINITAB 17) was used. The experimentation was repeated with and without oil to identify the significant parameters affecting the micro hardness level (Hv).

1. Introduction

The influence of the electro-magnetic field on the surface properties was noted earlier in United States in the 1930s’. The first patent was filed by Harry P. coats in the 1940s[1]. The main principle of MAF relies on magnetic field to control the mass of ferromagnetic powder to form a magnetic brush which is used to remove a thin layer from the surface of the workpiece[2]. The main advantages of MAF is, a good surface finish, ability to operate on bothmagnetic and non-magnetic materials and it leaves an excellent surface finish[3,4]. It was learnt that varying the following parameters on the MAF: amount of the powder, gap between pole and the work piece, pole diameter, pole rotational speed, current have the most signification impact[5-9].

Figure 2 demonstrates a schematic view of the image shown in Figure 1. The critical items to notice is the equipotential lines and the magnetic abrasive brush. It can be noticed how the workpiece or specimen are brushed by the particles which ensure a smooth finish is achieved.

The high-quality surface finish can be obtained by filing, polishing, grinding, lapping and honing methods. The method recently developed for finishing many surface types is MAF. It’s been determined that the method is efficient and accurate as well as a precise finishing is obtained. Using conventional methods, the super finishing is difficult to achieve as high pressure is required which runs the risk of damaging the material or surface. The traditional methods also not useful when trying to finish complex shapes and3d structures.

The main input parameters for a MAF are:

I. Work piece;
II. Rotational speed of magnetic field;
III. abrasive particles;
IV. Magnetic flux density;
V. Magnetic pole geometry;
VI. Finishing time;
VII. Oil.

Figure 1: Photographic brush formed by MAF process

Figure 2: Schematic view of the Magnetic Abrasive Finishing Process
The magnetic flux density is responsible for process. The change in input current quantity can vary the magnetic flux density. The current is supplied to magnet the abrasive flux. The magnetic field lines pass from the pole through magnetic abrasive particles. The abrasive particles move around the ferromagnetic particles. The unbounded magnetic abrasive particles are joined along the magnetic lines of force and form brush between workpiece and magnetic pole. Multipoint cutting tool is generated during this process.

In this work a study on the effectiveness of viscosity on MAF was undertaken. A few researchers have used liquid as for cooling or for the purpose of lubrication [10 and 11]. In this paper oil was used as a medium for undertaking the process of MAF. The main objective was to find the optimum parameters (for powder & oil viscosity) to improve the micro hardness and improve the surface.

2. Taguchi design of experiments for viscosity in MAF process

2.1 Selection of parameters, their levels and orthogonal array (OA)

To determine the hardness of the material the Vickers hardness test will be implemented. Vickers test is relatively less complex to use compared to the other hardness measurement tests. Vickers test can be implemented for all metals and has the widest scale. The unit of Vickers test is known as Vickers Pyramid Number represented by the symbol HV. This unit can be converted to SI units hence the values if needed can be computed in Pascals.

In this paper six parameter was taken, each parameter has three levels of variance, (density (amount of the powder), viscosity, pole diameter, working gap, rotational speed, current) the selection factors according primary experiments Table 1 are listed the number of experiments to find the condition that produces the optimum surface micro-hardness Taguchi orthogonal array was used. To implement the methodology of the test the flow chart in Figure 3 was implemented.

Figure 3 demonstrates the stages undertaken to implement the testing process. The variable “N” used in the flow chart indicates the experiment number. The experiment numbers are listed in Table 1 and Table 2. If Oil was not added to the test, then Table 1 is applicable whereas in the event Oil was used Table 2 becomes applicable. It can be noticed that in total 27 experiments were run with each parameter having 3 sets of variances. To run all the possible permutation would require \((3^6=729)\) 729 tests which would require extensive hours of testing. To reduce the number to a reasonable experiment the parameter density was given the most significance. As density is the most crucial parameter.

In total the 27 tests were run twice, once with the oil and once without the oil. At the end of each test the Vickers hardness, SNR and average were computed. The results for these tests are listed in the Table 1 and Table 2.
Figure 3: Testing Flowchart
Table 1: Taguchi orthogonal array with the experimental results of micro-hardness after (magnetic machining finishing) with oil. (The viscosity column was moved to the end of columns for the purpose of simplifying the study and to ensure the same code for the entire research. The viscosity column was after the doze column (all the parameters after was shifted)).

| Exp. | Doze | dia. | Gap | Speed | Current | Viscosity | Hv | SNRA1 | MEAN |
|------|------|------|-----|-------|---------|-----------|----|-------|------|
|      | A    | B    | C   | D     | E       | F         |     |       |      |
| 1    | 5    | 40   | 1   | 110   | 1       | 40        | 97.997 | 39.8242 | 97.997 |
| 2    | 5    | 40   | 1   | 520   | 1.5     | 40        | 98.507 | 39.8693 | 98.507 |
| 3    | 5    | 40   | 1   | 930   | 2       | 40        | 93.880 | 39.4515 | 93.880 |
| 4    | 5    | 48   | 1.5 | 110   | 1       | 200       | 99.727 | 39.9762 | 99.727 |
| 5    | 5    | 48   | 1.5 | 520   | 1.5     | 200       | 95.977 | 39.6433 | 95.977 |
| 6    | 5    | 48   | 1.5 | 930   | 2       | 200       | 96.433 | 39.6845 | 96.433 |
| 7    | 5    | 56   | 2   | 110   | 1       | 350       | 101.800 | 40.1550 | 101.800 |
| 8    | 5    | 56   | 2   | 520   | 1.5     | 350       | 99.320 | 39.9407 | 99.320 |
| 9    | 5    | 56   | 2   | 930   | 2       | 350       | 101.930 | 40.1660 | 101.930 |
| 10   | 10   | 48   | 2   | 110   | 1.5     | 40        | 102.533 | 40.2173 | 102.533 |
| 11   | 10   | 48   | 2   | 520   | 2       | 40        | 98.613 | 39.8787 | 98.613 |
| 12   | 10   | 48   | 2   | 930   | 1       | 40        | 98.257 | 39.8472 | 98.257 |
| 13   | 10   | 56   | 1   | 110   | 1.5     | 200       | 100.773 | 40.0669 | 100.773 |
| 14   | 10   | 56   | 1   | 520   | 2       | 200       | 102.467 | 40.2117 | 102.467 |
| 15   | 10   | 56   | 1   | 930   | 1       | 200       | 102.700 | 40.2314 | 102.700 |
| 16   | 10   | 40   | 1.5 | 110   | 1.5     | 350       | 99.367 | 39.9448 | 99.367 |
| 17   | 10   | 40   | 1.5 | 520   | 2       | 350       | 95.960 | 39.6418 | 95.960 |
| 18   | 10   | 40   | 1.5 | 930   | 1       | 350       | 96.620 | 39.7013 | 96.620 |
| 19   | 15   | 56   | 1.5 | 110   | 2       | 40        | 105.867 | 40.4952 | 105.867 |
| 20   | 15   | 56   | 1.5 | 520   | 1       | 40        | 106.267 | 40.5280 | 106.267 |
| 21   | 15   | 56   | 1.5 | 930   | 1.5     | 40        | 102.410 | 40.2068 | 102.410 |
| 22   | 15   | 40   | 2   | 110   | 2       | 200       | 99.820 | 39.9844 | 99.820 |
| 23   | 15   | 40   | 2   | 520   | 1       | 200       | 100.487 | 40.0422 | 100.487 |
| 24   | 15   | 40   | 2   | 930   | 1.5     | 200       | 99.953 | 39.9959 | 99.953 |
| 25   | 15   | 48   | 1   | 110   | 2       | 350       | 103.867 | 40.3296 | 103.867 |
The software which was used to find the Taguchi orthogonal array (OA) was Minitab 17.

2.2 Taguchi design of experiments without viscosity in MAF process

Without the viscosity there were only five parameters, with three levels of variance. Table 2 listed the experiment and results after MAF process parameters.

Table 2: Taguchi orthogonal array with the results of micro-hardness and without oil after different finishing

| Exp. | Doze | Diameter | Gap | Speed | Current | Hv  | SNR  | MEAN |
|------|------|----------|-----|-------|---------|-----|------|------|
|      | A'   | B'       | C'  | D'    | E'      |     |      |      |
| 1    | 5    | 40       | 1   | 110   | 1       | 101.933 | 40.1663 | 101.933 |
| 2    | 5    | 40       | 1   | 110   | 1.5     | 104.367 | 40.3713 | 104.367 |
| 3    | 5    | 40       | 1   | 110   | 2       | 102.167 | 40.1862 | 102.167 |
| 4    | 5    | 48       | 1.5  | 520   | 1       | 103.024 | 40.2588 | 103.024 |
| 5    | 5    | 48       | 1.5  | 520   | 1.5     | 103.033 | 40.2595 | 103.033 |
| 6    | 5    | 48       | 1.5  | 520   | 2       | 103.200 | 40.2736 | 103.200 |
| 7    | 5    | 56       | 2    | 930   | 1       | 101.687 | 40.1453 | 101.687 |
| 8    | 5    | 56       | 2    | 930   | 1.5     | 102.767 | 40.2371 | 102.767 |
| 9    | 5    | 56       | 2    | 930   | 2       | 101.287 | 40.1111 | 101.287 |
| 10   | 10   | 40       | 1.5  | 930   | 1       | 103.667 | 40.3128 | 103.667 |
| 11   | 10   | 40       | 1.5  | 930   | 1.5     | 103.067 | 40.2624 | 103.067 |
| 12   | 10   | 40       | 1.5  | 930   | 2       | 102.493 | 40.2139 | 102.493 |
| 13   | 10   | 48       | 2    | 110   | 1       | 102.255 | 40.1937 | 102.255 |
| 14   | 10   | 48       | 2    | 110   | 1.5     | 102.355 | 40.2022 | 102.355 |
| 15   | 10   | 48       | 2    | 110   | 2       | 103.200 | 40.2736 | 103.200 |
| 16   | 10   | 56       | 1    | 520   | 1       | 100.267 | 40.0232 | 100.267 |
| 17   | 10   | 56       | 1    | 520   | 1.5     | 98.593  | 39.8769 | 98.593  |
| 18   | 10   | 56       | 1    | 520   | 2       | 99.230  | 39.9329 | 99.230  |
3 Experimental work of the MAF process

Brass alloy is the material that was used as a work piece of this experiment, the dimensions of the flat surface work piece are (100x50x3) mm as shown in fig. 2. The mechanical properties and the chemical composition are listed in table 3 and 4 respectively.

Table 3: Mechanical properties of brass alloy (CuZn28)

| Type   | Tensile strength Kg/mm² | Vickers’s hardness | Density Kg/mm³ | Shear strength Kg/mm² |
|--------|-------------------------|--------------------|----------------|-----------------------|
| CuZn28 | 38-39                   | 98-105             | 84             | 28                    |

Table 4: Chemical composition of brass alloy (CuZn28)

| Type   | C  | Si | Mn | Cr | Ni | Mo | Zn  | Ti | Cu  | Fe  | Sn | Mg |
|--------|----|----|----|----|----|----|-----|----|-----|-----|----|----|
| CuZn28 | -- | -- | -- | -- | -- | -- | 28.2| -- | 70.7| 0.95|-- | -- |

In this work, three levels of viscosities were used (40,200,350) which were calculated by Ostwald's viscometer. The oil was placed at a tank to contain the mixture of oil and the powder of tungsten carbide (WC) with free iron and the oil, with the work piece submerged. This tank was used to contain the oil and control the powder particles from leaving the magnetic field. To cancel the waste of the powder that occurs because of the centrifugal force on the particles. Magnetic abrasive finishing inductor was setup as "vertical milling machine model MDM 4VS/HS/4S". The coil has 4500 turns, material of the core is C15 low carbon, the diameter of the wire is 0.9mm, the oil in the tank amount was 60 ml, and also there was one power supply for the current.
Figure 4: Brass Alloy Dimension

Figure 5: MAF Machine

4 Results and discussions

4.1 Signal–to noise ratio (SNR) technique in Taguchi method

There are many categories of the performance characteristics which can be employed to analyse SNR. A larger objective function was chosen to maximize the response. The SNR for this function calculated using the following formula:

$$\eta = - \log_{10} \left( \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right)$$
where $\eta$ denotes SNR values, $n$ is the total number of experiments and $y_i$ represented the value of the hardness at that run, the mean squared deviation MSD by using statistical software (Minitab 17) [12]

$$MSD = \frac{1}{n} \sum_{i=1}^{n} \left( \frac{1}{y_i} \right)$$

4.1.1 Analysis of the change in hardness for the oil content experiments

The change in the hardness of the flat surface is considered as an improvement of the surface of the workpiece. The results have been analysed by using the Taguchi method to find the optimal level for the six parameters. Based on the higher SNR, the maximum value of the change in hardness is determined. For each test, the mean value of hardness and SNR are given in Table 3. The main effects of the mean values at three different variances are calculated and given in Table 5 and Table 6 Respectively.

A comparison of the means with and without oil yielded a clear indication that use of oil reduced the mean value.

![Mean with and without Oil](image)

*Figure 6: Mean comparison with and without Oil*

From Figure 6 it can be noticed that the use of oil reduced the mean values. Regardless of the parameters the average values of the mean remain lower when compared to the experiments run without oil.

For each parameter the mean values have been rearranged to analyse the trends of change, this can be noticed in Figure 7. From the figures it can be noticed that change in diameter, density and current have the most significant impact on the mean.
Figure 7: Mean values compared with each parameter
Table 5: Response Table for Means with oil

| Level | A   | B   | C    | D    | E    | F    |
|-------|-----|-----|------|------|------|------|
| 1     | 98.40 | 98.07 | 100.47 | 101.31 | 100.83 | 100.48 |
| 2     | 99.70 | 99.94 | 99.85 | 100.13 | 99.92 | 99.82 |
| 3     | 102.53 | 102.6 | 100.30 | 99.18 | 99.87 | 100.33 |
| Delta | 4.13 | 4.5 | 0.63 | 2.12 | 0.96 | 0.67 |
| Rank  | 2   | 1   | 5    | 3    | 4    | 6    |

Table 6: Response Table for Signal to Noise Ratios with oil

| Level | A    | B    | C    | D    | E    | F    |
|-------|------|------|------|------|------|------|
| 1     | 39.86 | 39.83 | 40.04 | 40.11 | 40.07 | 40.04 |
| 2     | 39.97 | 39.99 | 39.98 | 40.01 | 39.99 | 39.98 |
| 3     | 40.21 | 40.22 | 40.03 | 39.93 | 39.98 | 40.03 |
| Delta | 0.36 | 0.39 | 0.06 | 0.19 | 0.09 | 0.05 |
| Rank  | 2   | 1   | 5    | 3    | 4    | 6    |

The tables above list the sequence of importance of each parameter in MAF process with the existence of oil along with the optimum levels. This information is represented in Figure 8.

Figure 8: The optimum levels of parameters (with oil).

From the table above the optimum results of hardness are obtained when the density ($A_3=15$) cc, pole diameter ($B_3=56$ mm), gap ($C_3=2$ mm), speed ($D_3=110$ rpm), current ($E_3=1$)
4.1.2 Analysis of the change in hardness for the oil absence experiments

The results have been analysed by using the Taguchi method to find the optimal level for the five parameters based on the highest SNR to give the maximum value of the change in hardness by MAF process. For each test, the mean value of hardness and SNR are given in Table 6. The main effects of the mean values at three different levels for and SNR are calculated and given in Table 7 and Table 8 respectively.

![Graphs showing mean values compared with each parameter](image)

Figure 9: Mean values compared with each parameter
From Figure 9 it can be determined that with the use of oil varying speed and density has the greatest impact on the mean values.

**Table 7:** Response Table for Means (without oil)

| Level | A'  | B'  | C'  | D'  | E'  |
|-------|-----|-----|-----|-----|-----|
| 1     | 102.6 | 103.3 | 100.7 | 101.9 | 101.7 |
| 2     | 101.7 | 101.8 | 102.1 | 102.2 | 102.1 |
| 3     | 101.4 | 100.5 | 102.8 | 101.6 | 101.9 |
| Delta | 1.2  | 2.8  | 2.2  | 0.6  | 0.4  |
| Rank  | 3    | 1    | 2    | 4    | 5    |

**Table 8:** Response Table for Signal to Noise Ratios (without oil)

| Level | A'   | B'   | C'   | D'   | E'   |
|-------|------|------|------|------|------|
| 1     | 40.22 | 40.28 | 40.06 | 40.16 | 40.14 |
| 2     | 40.14 | 40.16 | 40.18 | 40.18 | 40.18 |
| 3     | 40.12 | 40.04 | 40.24 | 40.14 | 40.16 |
| Delta | 0.11 | 0.24 | 0.19 | 0.05 | 0.03 |
| Rank  | 3    | 1    | 2    | 4    | 5    |

The tables above give the sequence of importance of each parameter in MAF process with the absence of oil, also it gives the optimum level because larger number gives the optimum level of each parameter. This information is represented in Figure 10.

The Figure 10 showed the condition to reach the optimum hardness can be obtained when density \(A'_3=15 \text{ cc}\), pole diameter \(B'_3=40 \text{ mm}\), gap \(C'_2=2 \text{ mm}\), speed \(D'_1=110 \text{ rpm}\), current \(E'_3=2 \text{ A}\).
Figure 10: The optimum variances of parameters (without oil)

4.2 Regression analysis

ANOVA method is used to clear the influence of parameters on micro hardness, and MINITAB 17 is used to find the significant parameters. R-sq value shows how much the method affected. Table 9 show the results of ANOVA with oil. Table 10 shows the results of ANOVA without oil.

Table 9: Analysis of Variance R-Sq analysis with oil

| Source | DF | Adj SS  | Adj MS  | F-Value | P-Value | Significant parameter | Parameters contribution % |
|--------|----|---------|---------|---------|---------|-----------------------|--------------------------|
| Regression | 6  | 194.526 | 32.4211 | 14.15   | 0.000   |                       |                          |
| A      | 1  | 76.773  | 76.7734 | 33.50   | 0.000   | Significant           | 39.4665                  |
| B      | 1  | 93.132  | 93.1321 | 40.64   | 0.000   | Significant           | 47.87613                 |
| C      | 1  | 0.134   | 0.1336  | 0.06    | 0.812   | Not Significant       | 0.068885                 |
| D      | 1  | 20.255  | 20.2547 | 8.84    | 0.008   | Significant           | 10.41244                 |
| E      | 1  | 4.125   | 4.1247  | 1.80    | 0.195   | Not Significant       | 2.120528                 |
| F      | 1  | 0.108   | 0.1078  | 0.05    | 0.830   | Not Significant       | 0.055519                 |
| Error  | 20 | 45.831  | 2.2916  |         |         |                       |                          |
| Total  | 26 | 240.358 |         |         |         |                       |                          |

Model Summary: R-sq = 81.25%
Regression Equation

\[ Hv = 96.89 + 2.445A + 2.071B - 0.499C - 1.314D - 0.800E - 0.328F \]

This equation gives the micro-hardness of the surface theoretically.

Table 10 Analysis of Variance R-Sq analysis without oil

| Source | DF | Adj SS  | Adj MS  | F-Value | P-Value | Significant parameter | Parameter contribution % |
|--------|----|---------|---------|---------|---------|------------------------|--------------------------|
| A      | 2  | 7.5314  | 3.7657  | 5.46    | 0.016   | Significant            | 11.28071                 |
| B      | 2  | 34.8802 | 17.4401 | 25.30   | 0.000   | Significant            | 52.24441                 |
| C      | 2  | 22.3157 | 11.1578 | 16.19   | 0.000   | Significant            | 33.425                   |
| D      | 2  | 1.3943  | 0.6971  | 1.01    | 0.386   | Not Significant        | 2.088417                 |
| E      | 2  | 0.6419  | 0.3209  | 0.47    | 0.636   | Not Significant        | 0.961453                 |
| Error  | 16 | 11.0302 | 0.6894  |         |         |                        |                          |
| Total  | 26 | 7.7935  |         |         |         |                        |                          |

Model Summary: R-sq= 85.82%

Regression Equation without oil

\[ Hv = 103.897 - 0.627A - 1.558B + 1.168C - 0.065D + 0.089E \]

This equation gives the micro-hardness of the surface theoretically.

Conclusions

The influence of the viscosity on the surface micro-hardness for the brass alloy via MAF process were investigated and the following conclusions can be deduced:

1. When the oil media was used the optimum results of hardness are obtained when the doze \((A_3=15)\) cc, pole diameter \((B_3=56)\) mm, gap \((C_3=2)\) mm, speed \((D_1=110)\) rpm), current \((E_1=1)\) and viscosity \((F_3=15)\). These levels of parameters gives \((Hv=110.1)\).
2. When the oil media wasn't used the optimum hardness can be obtained when doze \((A'_3=15)\) cc, pole diameter \((B'_3=40)\) mm, gap \((C'_2=2)\) mm, speed \((D'_1=110)\) rpm) and current \((E'_3=2)\) A. These levels of parameters gives \((Hv=108.4)\).
3. With oil the surface micro-hardness is much better than without oil.
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