MICROMACHINING THE INNER SURFACE USING MAGNETIC ABRASIVE FINISHING PROCESS IN MAGNETIC FIELD OF A STATOR AND STUDY ON THE EFFECTS OF INPUTE PARAMETERS ON ROUGHNESS CHANGES WITH DOE TECHNIQUE

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Abstract: In this research paper, a new method called MAF-S process was used for micromachining the inner surfaces of pipes. Magnetic Assisted Finishing process is a surface finishing technique in which a magnetic field is used to force abrasive particles against the target surface. Recently, this process has attracted the researchers. As an extension of MAF process for the finishing of cylindrical surfaces, MAF-S process was introduced. In this approach, by using the magnetic field of a stator, magnetic abrasive particles were wrought as magnetic rods and surface micromachining was carried out by the dynamic particular pattern made by a stator magnetic field. The aim of this process was to improve machining efficiency of Aluminum pipes based on surface roughness and tolerance parameters. By continuously using the DOE technique (Design of Experiments), the effects of parameters such as pipe inner diameter, abrasive particles weight, frequency and machining time on the changes of surface roughness were investigated. Taguchi standard orthogonal method (L_9 (3^4)), which was associated with nine experiments, was used to analyze the factors. Then, two most widely used analytical techniques including Signal to Noise ratio (S/N) and Analysis of Variance (ANOVA) were used to analyze the output results derived from experiments by powerful statistical SPSS software. Finally, by considering the results of analysis and graphs plotted, abrasive particles weight and frequency were identified as significant and the optimum of pipe inner diameter of 55 mm, abrasive particles weight of 1 g, frequency of 40 Hz and machining time of 60 s were obtained.

Key words: magnetic assisted finishing, MAF, MAF-S process, stator, micromachining, DOE technique.

1. INTRODUCTION

Due to the presence of surface defects resulting from manufacturing processes, scientists and industries have tried to obtain the surface without the drawbacks such as crystal surface defects, micro cracks and chemical pollution resulting from traditional processes such as Thermal operating, Grinding, Honing and Lapping and nontraditional processes such as Electrical Discharge Machining (EDM), Electrochemical Machining (ECM), Electron Beam Machining (EBM) and Laser. Therefore, they have designed final machining processes for removing surface defects, increasing workpiece fatigue life and improving surface roughness. Generating the surfaces with geometric precision and high-level quality and without surface micro cracks in sensitive and accurate industries such as biotechnology, semiconductors, optics and air-space are very important (McGeough, 1988; Kang et al., 2012; Lin et al., 2007). Magnetic Assisted Finishing (MAF) process is a final machining process with abrasive particles that can move to the magnetic abrasive particles under the generated magnetic field and remove material from surface to obtain better surface roughness, which is impossible to get by using traditional methods. In recent years, more scientists have attempted to develop MAF process, Wang and Hu (2012) examined MAF process on different kinds of materials and reported that among aluminum alloy LY14, stainless steel 316L and brass H82, brass has the highest level of material removal rate. Kang et al. (2012) introduced a high-speed multipolar system and studied the effects of rotational speed on machining the inner surface of capillary pipe. They showed that velocity of 10000 rpm was optimal to obtain optimal surface roughness. Lin et al. (2007) used the DOE technique with Taguchi method to describe the effects of magnetic field, spindle rotational speed, feed rate, gap, abrasive particles and the lubricant on MAF process of stainless steel SUS 304. It improved the primary R_a = 2.670 μm to R_a = 0.158 μm by using MAF process. Mori et al. (2003) tested the magnetic field of active forces in their paper and explained the base of MAF process. Jaswal et al. (2005) studied the theory of MAF process and analyzed the distribution of magnetic forces on the workpiece surface using the finite element method. Givi et al. (2012), using the rotation of the permanent poles on the back of the aluminum sheet, performed high level surface machining of aluminum sheet. They studied parameters such as abrasive particles weight, gap, rotational speed of poles and the number of cycles on the surface roughness changes (ΔR_a) by using the factorial method. They introduced the number of cycles and gap as the most effective parameters. Girma et al. (2006) revealed that machining mechanism of cylindrical and flat surfaces was different. According to their results, obtaining high-quality level in the cylindrical inner surface is more difficult, requiring more investigation to promote the obtained surface quality by creating some changes in this process.

In this research, we firstly introduced a new method called MAF-S process for micromachining the inner surface of Aluminum pipes under the magnetic field made by a stator. Secondly, by using DOE technique, the effects of pipe inner diameter, abrasive particles weight, frequency and machining time on the changes of surface roughness (ΔR_a) were studied and the optimal quantity for each one was determined. Improvement in the surface quality with controlled minimum material removal helped to maintain dimensional tolerances not considered seriously in the previous researches. As already mentioned, machining process assisted with abrasive particles is a group of final machining processes and it is important to maintain the generated tolerances in the previous stages in high accuracy machining processes. Compared to MAF process, MAF-S process has such advantages as: No limitation in velocity range of abrasive particle and the workpiece size at high speed due to lack of relative motion between poles and workpiece. Other characteristics of this process include the presence of a special adjustable pattern in material removal which is transformable from MAF-S to MAF, portable and does not need machines such as milling and turning machines, thus lowering the manufacturing expenses and making it accessible for individuals. In addition, the similar efficiencies with MAF, MAF-S process make it possible to machine and to clean fluid transmission lines constricted due to sediments without any need to open them.

2. EXPERIMENTAL SETUP

Manufactured apparatus for MAF-S process consists of a stator of periodical electric motor or a stepper motor, an inverter, and a chuck for clamp packaging. Figure 1 shows MAF-S device. Stator generates the requisite magnetic field and inverter regulates the rotational speed of the abrasive particles by setting up the input frequency to stator. It has been taken from AC stator, inverter RHYMEBUS (RM5E-2002), extruded pipes from aluminum AA6063 and abrasive particles from steel in MAF-S process (Table 1).

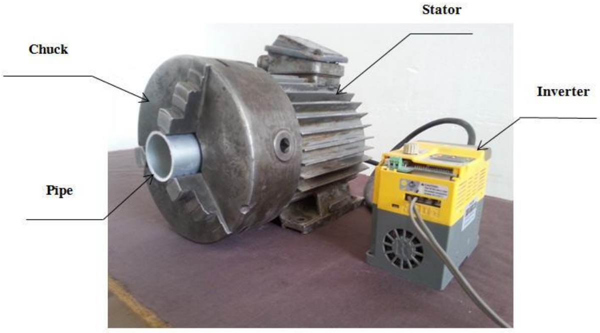

Fig.1. The image of MAF-S Device

Table 1. Details of Experimental Tools and Materials

Explain	
Stator	1.1 Kw, Cos φ=0.88, 2890rpm, 50Hz, 2.3/4A, Internal Diameter 8 mm
Inverter	RHYMEBUS, RM5E-2002
Aluminum pipe	AA6360, Length 300mm, Primary Roughness 0.3 - 0.8 µm
Abrasive Particles	GL120, Hardness 50-60 HRC, Density 7g/cm^3, mesh size (0.125-0.3)mm, Chemical detail: Carbon 0.85-1.2%, Silicon 0.40%, Manganese 0.60-1.20%, Sulfur 0.05% MAX, Phosphorus 0.05% MAX.

3. MATERIAL REMOVAL MECHANISM

In the MAF-S process, Aluminum pipe with abrasive particles was placed inside the stator (concentric). Subsequently, by applying a current, the magnetic field was created in the coil of the stator and the formation of abrasive particles as clusters along the magnetic field, called Magnetic Rods (MRs), was accomplished under the created magnetic field (Figure 2). These MRs were placed along the new magnetic field by changing the current from a coil to an adjacent coil. Therefore, MRs had two kinds of motion including the rotation around their axis, parallel to the axis of the pipe, and rotation around circumference of pipe inner surface. Most material removal is performed in both edges of MRs due to the combination of the above two motions. Length of MRs is various; thus friction in different points happens accidentally. This increased the surface quality. MAF-S process can be transformed to MAF process and this is acquired with increasing the frequency and/ or changing the size of abrasive particles. It is necessary to mention that material removal in MAF system is more than MAF-S system. It could be explained that as a result of the increase in input frequency, length of MRs is decreased; thus the number of MRs and cutting edges is increased. Material removal is increased with increasing the cutting edges. The more increase in frequency leads to slide motions of MRs and this happens in the MAF system.

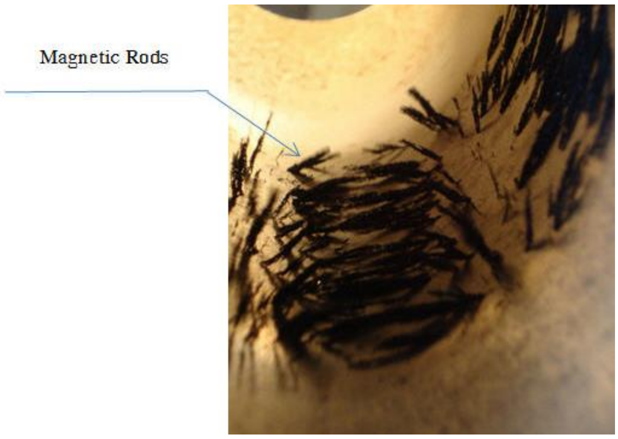

Fig. 2. Formation of Magnetic Rods (MRs) inside the Alumium pipe, at the Bigining of MAF-S process with low frequency

4. EXPERIMENTAL PROCEDURE

Experiments performed to evaluate four input parameters included pipe inner diameter, abrasive particles weight, frequency and machining time on the output parameter (ΔR_a) (Table 2). In order to improve the measured parameters, pipes were firstly cut into two parts and roughness was measured in two points of inner surface by using the roughness tester Mahr Set M300-RD18. Then, the parts were stuck together and placed in MAF-S apparatus. By tightening up the pipe in the chuck, pipe and stator became coaxial. Abrasive particles were weighed with the accuracy 0.001 gram and poured into the pipe. Subsequently, the desired frequency was adjusted using the inverter and machining time was measured. For any test, the surface roughness was measured at two points marked and the amount of ΔR_a for any point was obtained by using the equation (1).

$$\Delta R_a = R_{a2} - R_{a1} \tag{1}$$

Table 2. Input parameters and their defined quantities used for Design of Experiment technique with Taguchi orthogonal standard method $L_9\ (3^4)$

	Factor	Type	Levels	Values
Pipe inner diameter (mm)	C1	fixed	3	30, 45, 55
Abrasive particles weight (g)	C2	fixed	3	1, 5, 9
Frequency (Hz)	C3	fixed	3	20, 30, 40
Machining time (s)	C4	fixed	3	30, 60, 90

5. DESIGN OF EXPERIMENTAL TECHNIQUE (DOE)

In this paper, Taguchi standard orthogonal method was used to evaluate four parameters including pipe inner diameter, abrasive particles weight, frequency and machining time. Each of parameters was defined in three levels. By using this method, the number of 3^4=81 tests was substituted by optimal 9 experiments to decrease the calculation time (Table 3). Performing the test by Taguchi standard orthogonal method was useful and it was better than the other methods. Also, the analysis of the acquired data from this method, in comparison with other methods, was simpler (Forouzan and Niroomand, 2012). The obtained results were analyzed by Signal to Noise ratio (S/N) method and optimum conditions were illustrated. Parameters significance was also studied by ANOVA method.

Table 3. Design of Experiments technique with Taguchi orthogonal standard method $L_9\ (3^4)$, ΔR_{a1} , ΔR_{a2} and calculated η for nine tests

No. crt.	Pipe inner diameter (mm)	Abrasive particles weight (g)	Frequency (Hz)	Machining time (s)	ΔR_{a1}	ΔR_{a2}	η
1	30	1	20	30	0.129	0.102	18.6894
2	30	5	30	60	0.088	0.122	19.4638
3	30	9	40	90	0.051	0.047	26.1888
4	45	1	30	90	0.079	0.005	25.0404
5	45	5	40	30	0.075	0.082	22.0940
6	45	9	20	60	0.065	0.067	23.6081
7	55	1	40	60	0.036	0.016	31.1014
8	55	5	20	90	0.269	0.102	13.8318
9	55	9	30	30	0.041	0.038	28.0618

5.1. Data Analysis

Optimizing technique was carried out using the Taguchi and Analysis of Variance (ANOVA) methods in analytical SPSS software. Also, the accuracy of experiments was investigated by depicting various diagrams.

5.1.1. Signal to Noise ratio (S/N)

Optimizing technique with Taguchi method was carried out by Signal to Noise ratio (S/N) method. In order to identify and obtain the optimal conditions among experiments, S/N method was used. After analyzing with S/N method, the best level was introduced for any factor. The main idea in S/N analyzing is that in the optimal conditions, operating sensitivity or output value into noises becomes minimal. On the other hand, there are optimal conditions under which changes in output values become more dependent on signal values than noise values (Forouzan and Niroomand, 2012). Therefore, S/N analyses specify optimal conditions in cases with maximum signal to noise ratio. Aim of this study was to decrease ΔR_a in order to increase surface roughness and keep tolerances. Thus, Smaller the Better (SBT) state was chosen. ŋ, as the analyzing parameter of S/N method in SBT state, is shown in equation (2).

$$\eta = -10 \log_{10} \left[1/n \sum_{i=1}^{n} y_i^2 \right] \tag{2}$$

y_i is the output value for i_{th}test and n is the number of repeat cycles. Thus, ŋ for any experiment related to a series of factors regulations is calculable. Among ŋ values, the larger value shows the optimal conditions (Table 3).

As shown in Table 3, maximum value ŋ was obtained in experimental test 7, which described how the parameters were optimized in this test. According to main effects plot (Figure 3), the maximum value in this diagram was the optimal value. Therefore, pipe inner diameter of 55mm, abrasive particles weight of 1g, frequency of 40Hz and machining time of 60s were optimal values in these tests.

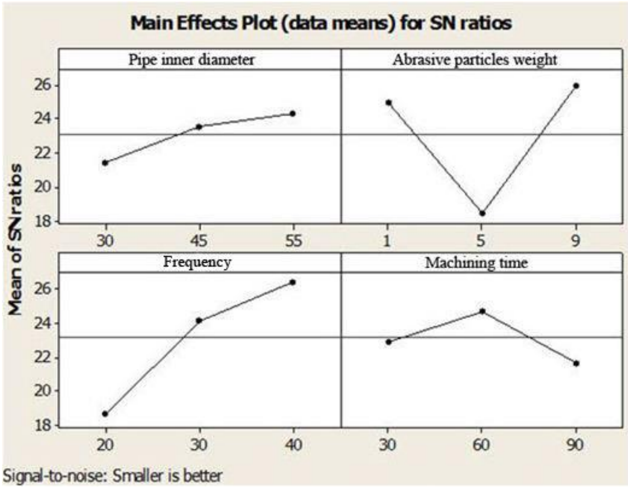

Fig. 3. Main effects plot in S/N Method

5.1.2 Analysis of Variance (ANOVA) Method

Analysis of Variance is a method used for covering the graphical assessments. The use of this method can clarify significant parameters and their effects on the process. On the other hand, while a parameter is significant, it has a remarkable effect on the process and insignificance of a parameter shows the negligible effect of the parameter in the process. Significant level was defined as P= 0.05 in the analyses and the parameter was significant for an amount lower than 0.05. Table 4 shows that both parameters of frequency and abrasive particles weight were significant. It is notable that both parameters of pipe inner diameter and machining time were also effective in the process, but their effect was negligible. According to Table 4, for ΔR_a, the values of R^2 (R-Sq) and total error squares (S) parameters were 69.29% and 0.0445, respectively. Desirable model is known to have a large value of R^2 (R-Sq) parameter and a small value of (S) parameter.

Table 4. Analysis of Variance for ΔR_a, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pipe inner diameter	2	0.002531	0.002531	0.001266	0.64	0.551
Abrasive particles weight	2	0.018058	0.018058	0.009029	4.55	0.043
Frequency	2	0.017611	0.017611	0.008806	4.44	0.046
Machining time	2	0.002111	0.002111	0.001056	0.53	0.605
Error	9	0.017864	0.017864	0.001985		
Total	17	0.058176				
S = 0.0445521						

In Figure 4, the residual plots for ΔR_a have been depicted as follows: Normal probability plot of the residuals, Residuals versus the fitted values, Histogram of the residuals, and the Residual versus the order of the data. One of the plots studied in relation to data validation is the normal probability plot of the residuals (Figure 4). In general, if all points tend to form a line, it means a normal distribution of the results. In this experiment, the points relatively placed on a line mean that the experimental outputs were approximately normal. However, in this experiment, due to the use of the DOE technique with Taguchi standard tables method, the normal factor was not much important. The plot of residuals versus the fitted values demonstrates the convergence and outputs normality. This plot shows a random pattern of the outputs in both sides of zero line (Givi et al., 2012). According to the plot, it is clear that the points didn't have any specific patterns, proving the variance constancy and data uniformity. Also, the histogram of the residuals and the residual versus the order of the data plots displayed points compression and the resulted consistency around the optimum status. According to the diagrams, it is clear that most experimental results with minimal errors were centered on the zero line.

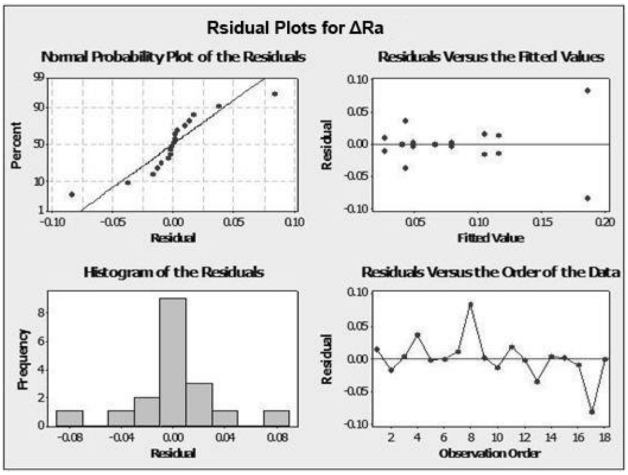

Fig. 4. Normal probability plot of the residuals, Residuals versus the fitted values, Histogram of the residuals and Residuals versus the order of the data

6. EXPERIMENTAL RESULTS

In this section, according to Figure 5, the effects of input parameters including pipe inner diameter, abrasive particles weight, frequency and machining time on the output parameter ΔR_a were investigated as follows.

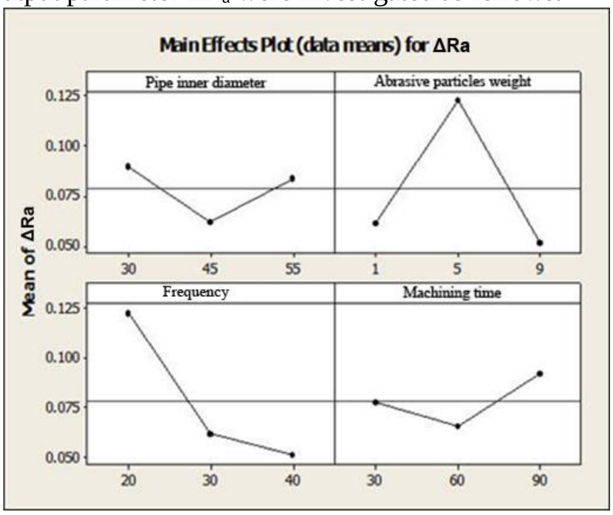

Fig. 5. Effect of pipe inner diameter, abrasive particles weight, frequency and machining time on ΔR_a in ANOVA method

6.1. Pipe inner diameter

According to Figure 5, it was observed that with increasing the pipe inner diameter to the inner diameter of the stator (80 mm), ΔR_a was initially decreased and then increased. It can be mentioned that the changes in ΔR_a versus the diameter were dependent on the direction of the magnetic field lines and their density. When pipe diameter was large and close to the inner diameter of stator, there were the parallel magnetic field lines, perpendicular to the workpiece surface and aggregate in this region. Thus, the magnetic field was powerful and formed the MRs extensively and stuck strongly to the surface and increased the rate of material removal, which, in turn, increased ΔR_a as well. Lines angles were oblique at mid-diameters and lines aggregation was lower. Thus, particles and MRs possessed less force for material removal and reduced their penetration in the workpiece and ΔR_a was decreased. Due to the presence of weak magnetic field in the small diameters, MRs formation faced the problem and their length was reduced much more and thus, the number of MRs was added. The cutting edges were increased along with the increase in the number of MRs, thus causing more material removal from surface than the previous case.

6.2. Abrasive particles weight

As shown in Figure 5, the maximum value ΔR_a took place in the weight 5g. MRs were not formed sufficiently in the weight of 1g due to insufficient abrasive particles; thus ΔR_a was small. The increase in abrasive particles weight and the passage of ΔR_a on its maximum point were due to accumulation of the particles on each other and also the distribution of the magnetic field to more particles; thus, power of material removal was reduced and consequently, ΔR_a was reduced too.

6.3. Frequency

As shown in Figure 5, with increasing the frequency, ΔR_a was declined, but in the frequency 30Hz, the chart slope was reduced. The minimum amount of ΔR_a in the frequency 40Hz was created. There was the sufficient time in the low frequency for material removal by MRs. Also it should be mentioned that in this frequency, MRs had more length and the acquired moment in both ends of MRs was large; thus MRs dis material removal too much and ΔR_a was high. The length of MRs was reduced along with increasing the frequency; due to this, there was not only enough time for friction, but also the acquired moment in both ends of MRs was reduced. This trend continued till reaching the frequency 30Hz, but with passing this frequency, MRs became shorter and MAF-S material removal system was converted to

MAF material removal system and particles movement was roughly turned into sliding movement. This was why the chart slope was reduced after frequency of 30 Hz and it was predicted to pass on the optimal point, thus making the chart slope positive.

6.4. Machining time

According to Figure 5, ΔR_a was reduced with increasing the machining time from 30s to 60s and ΔR_a was increased in the range of 60 s to 90 s. In the Range of 30s to 60s, flat surface was obtained with removing the peaks by MRs and ΔR_a reached to 0.016μm. After passing on 60s, due to the low surface roughness, besides removing the peaks, somewhat, the valleys were material removed by MRs and therefore, ΔR_a changes were increased. According to the acquired results, optimum time was 60s for this test, identical with results of S/N analysis. However, this parameter was not significant; therefore, its changes did not have a significant effect on the process.

7. CONCLUSION

It has been tried to reduce ΔR_a as controlled and keep the workpiece tolerances with the design and innovation of a new method called MAF-S process. It was observed by using the magnetic field produced by a stator in the cylindrical inner surface of aluminum pipe, with a minimum material removal of the surface; in addition to improvement in the surface roughness, tolerances with high precision were preserved. By using the S/N method and keeping the maximum amount ŋ equal to 31.1014, optimal values of the parameters in this experiment were obtained as pipe inner diameter of 55mm, abrasive particles weight of 1g, frequency of 40Hz, and machining time of 60s. Abrasive particles weight with P= 0.043 and frequency with P= 0.046 were identified as the effective controllable parameters using the ANOVA method. The quantity R^2 (R-Sq) was equal to 69.29%, indicating a high grade of desirable model. According to the chart of the residuals versus the order of the data and dispersal of points without pattern around zero line, both constancy and uniformity of variance were provable. According to the observations, it different patterns can be obtained for surface machining by appropriate pipe inner diameter to stator inner diameter ratio. Changes in abrasive particles weight showed that the best surface quality was created in the weight 5g, but this weight was far from the aim of experiment, which was maintaining the accuracy in controlling tolerances and micromachining operations. It seems that at low frequencies, the quality of produced surfaces was more by considering the high amount of ΔR_a and tolerances were more prone to be changed. The increase in frequency was accompanied with the decrease in the level of surface quality, but the tolerances were being maintained with more precision. The aim of this research was to maintain tolerances in the micromachining operations and improve the surface roughness used in the MAF-S process.

8. REFERENCES

1. Forouzan, M. R., Niroomand, M. R., (2012). *Recent Optimization Methods,* Second edition, pp. 105-150, Jahad Daneshgahi of Esfahan, Esfahan.
2. Girma, B., Joshi, S.S., Raghuram, M.V.G.S., (2006). *An experimental analysis of magnetic abrasives finishing of plane surfaces,* Mach. Sci. Technol., 10, 323-340.
3. Givi, M., FadaeiTehrani, A., Mohammadi, A., (2012). *Polishing of the aluminum sheets with magnetic abrasive finishing method,* Int. J. Adv. Manuf. Technol, 61, 989-998.
4. Jayswal, S.C., Jain, V.K., Dixit, P.M., (2005). *Modeling and simulation of magnetic abrasive finishing process,* Int J. Adv. Manuf. Technol., 26, 477-490.
5. Kang, J., George, A., Yamaguchi, H., (2012). *High-speed Internal Finishing of Capillary Tubes by Magnetic Abrasive Finishing,* Procedia CIRP, 1, 414–418.
6. Lin, C.T., Yang, L.D., Chow H.M., (2007). *Study of magnetic abrasive finishing in free-form surface operations using the Taguchi method,* The International Journal of Advanced Manufacturing Technology, 34, 122-130.
7. McGeough, J.A., (1988). *Advanced Methods of Machining*. pp. 1-274. Chapman and Hall Ltd, New York.
8. Mori, T., Hirota, K., Kawashima, Y., (2003). *Clarification of magnetic abrasive finishing mechanism,* Journal of Materials Processing Technology, 143–144, 682–686.
9. Wang, Y., Hu, D., (2012). *Study on Inner Surface Finishing of Tubing by Magnetic Abrasive Finishing,* International Journal of Machine Tools and Manufacture, 45, 43–49.

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