The International Journal of Materials and Engineering Technology (TIJMET) (2023) 6(1)
http://dergipark.gov.tr/tijmet
ISSN: 2667-4033

RESEARCH ARTICLE

Validation of material model and mechanism of material removal in abrasive flow machining

Omer Eyercioglu*[1], Kursad Gov[2] and Adem Aksoy[3]

[1]Gaziantep University, Faculty of Mechanical Engineering, Department of Mechanical Engineering, Gaziantep, Türkiye
[2]Gaziantep University, Faculty of Aeronautics and Astronautics, Aerospace Engineering Department, Gaziantep, Türkiye
[3]Gaziantep Islam Science and Technology University, Vocational School of Technical Sciences, Gaziantep, Türkiye

Article Info

Article history:
Received: 18.01.2023
Revised: 12.05.2023
Accepted: 24.05.2023
Published Online: 26.05.2023

Keywords:
Abrasive flow machining
Surface finishing
Mathematical modeling
CFD analysis of AFM

Abstract

Abrasive flow machining (AFM) is a non-traditional surface finishing method that is recently becoming popular. Increasing surface quality demands and developing manufacturing technologies need high costs and time. AFM process satisfies these demands in a short time period. In this study, the material removal model for a double-acting AFM and the experimental validation of the model was presented. The material removal model was based on the previously performed mathematical studies and the active grain numbers and the total material removal formulations were re-evaluated. A CFD analysis was carried out to determine the wall shear stress, velocity distribution, static and dynamic pressure values and used in the mathematical model. The experimental study is performed on the Ti-6Al-4V alloy using 400 mesh size SiC abrasive for 20%, 40%, and 60% abrasive concentrations by weight. The results of the experimental study were compared with the results of the mathematical model presented in the study. The differences between the results of the presented model and the experimental ones are very close to each other for all abrasive concentrations. By using the presented model, the AFM process parameters can be pre-determined according to the required final form.

1. Introduction

Abrasive flow machining (AFM) is a non-traditional finishing method that is recently becoming popular [1-4]. AFM method is successfully applied to medical, aerospace, and other precision manufacturing areas [5]. Increasing surface quality demands and developing manufacturing technologies need high cost and time. AFM process satisfies these demands in a short time period [6]. In the AFM method, complex geometries and difficult-to-reach surfaces can be processed more easily than traditional methods [7, 8].

The AFM process is performed by extrusion of the polymeric media between two reciprocating pistons in cylinders (Figure 1). The polymeric media contains abrasive particle, hydraulic oil, water, and a polymeric material. Media flows through the surface of the workpiece at high pressure [9]. The surface is getting smoother and cleaner after AFM process [6]. This process is effective for mostly the parts manufactured by wire electrical discharge machined (WEDM) surfaces [10].

Types of workpiece materials and material properties influence surface roughness after the AFM process [11]. The studies which are experienced on Ti-6Al-4V [12, 13] and AISI D2 hardened tool steel show that AFM process has better results on harder materials [14, 15]. The residual asperities are getting smoother or entirely removed without any change in geometry by AFM method [16]. Viscosity, abrasive concentration, abrasive type, and mesh size are effective parameters in the process. Abrasive media generally includes abrasive particles as silicon carbide (SiC) particles [17, 18]. Besides, aluminum oxide, boron carbide, or garnet are used as an abrasive particle.

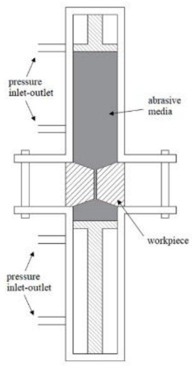

Figure 1. Abrasive Flow Machine (AFM) model

Jain et. al. [19] examined the AFM media parameters and showed that the viscosity of media is proportional to the temperature, concentration and mesh size of the abrasive. Media viscosity is directly proportional to the abrasive concentration and inversely proportional to the abrasive mesh and temperature. In addition, they found that higher viscosity results in higher material removal and improved surface quality.

Modeling is conventionally an effective method to design and analyze a process or a product and it is considered beneficial while designing improvements for increasing process performances. In the late 1980s, many efforts were done to a material removal mechanism and surface generation modeling of the AFM operation [20]. For the analysis of flow, computational fluid dynamics (CFD) is one of the most popular simulation methods. Widely used analysis tools such as ANSYS FLUENT have been preferred by various researchers [21].

Corresponding Author: Omer Eyercioglu
E-mail: eyercioglu@gantep.edu.tr

How to cite this article:
Eyercioglu, O., Gov, K., and Aksoy, A., Validation of material model and mechanism of material removal in abrasive flow machining, The International Journal of Materials and Engineering Technology (TIJMET), 2023, 6(1): 7-11

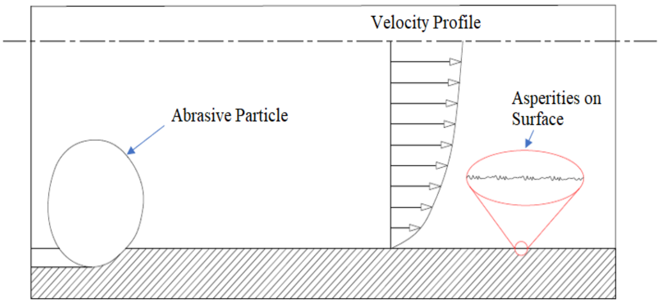

Figure 2. Material removing model

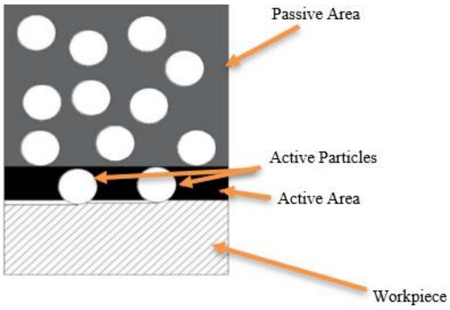

Figure 3. Active and passive areas-particles

Rajeshwar et. al [22] carried out modeling and simulation studies of the AFM process. They used primary equations of the Maxwell model to define the non-newtonian flow characteristics of the AFM media for the cylindrical workpiece. In another study, the interaction between workpieces and abrasive particles was examined [23]. They have shown that a higher concentration of abrasives produces better surfaces and higher material removal. The finite element method was used to determine the velocity and stress distribution in the AFM process [24]. The velocity and pressure distribution inside the flow geometry can be obtained from CFD simulation. The velocity is maximum at the center and minimum near the walls. The pressure decreases gradually after passing from the inlet to the exit [25].

In this study, the material removal model for a double-acting AFM and the experimental validation of the model was presented. The material removal model was based on the mathematical model suggested by Jain et.al [4] and the active grain numbers and the total material removal formulations were re-evaluated. The experimental study was performed on the Ti-6Al-4V alloy using 400 mesh size SiC abrasive material for abrasive concentrations of 20%, 40% and 60% by weight. A CFD analysis was carried out to determine the wall shear stress, velocity distribution, static and dynamic pressure values and used in the mathematical model. The amount of metal removal from the workpiece surface was investigated at different abrasive concentrations. The results of the experimental study that was previously done for Ti-6Al-4V alloy [26] were compared with the results of the mathematical model presented in this study.

2. The mechanism of material removal and the mathematical model

2.1 The mechanism of material removal

In the AFM process, the material removals occur by the motion of the particles (Figure 2). Particle size and shapes are different but all particles assumed as circular or near-circular shaped in the modeling. The particles are near the surface of the workpiece called active particles. Active particles remove the surface of the workpiece (Figure 3).

2.2. The Mathematical Model of the Material Removal

The material removal model is based on the mathematical model suggested by Jain et.al [13]. The active grain numbers and the total material removal formulations were re-evaluated.

The force (F) acting on the abrasive grain produces an indentation and the plastically deformed zone rises upward. When the media flows through the surface at high pressure, the abrasive grain shears the plastically displaced material and forms a chip. To obtain the actual diameter of the abrasive from mesh size to millimeter:

$$d_g = \frac{28}{M^{1,1}} \quad (1)$$

The vertical force component (indenting force) on the grain with a diameter (dg) is calculated by

$$F = \sigma \frac{\pi d_g^2}{4} \quad (2)$$

where σ is wall shear stress acts on the abrasive grain. Taking a as the radius of the indentation projected area (ΔA), and H_w as the workpiece material hardness, the force can be expressed as:

$$F = H_w \Delta A = H_w \pi a^2 \quad (3)$$

The indentation depth (t) and the radius (a) can be obtained from Figure 4 as:

$$a = \sqrt{\frac{F_r}{H_w \pi}} \quad (4)$$

$$t = \frac{d_g}{2} - \sqrt{\left(\frac{d_g^2}{4} - {r_a}^2\right)} \quad (5)$$

and

$$a = \sqrt{t(d_g - t)} \quad (6)$$

The indentation depth (t) is finally expressed by substituting a from Eqn. (4) into Eqn. (5);

$$t = \frac{d_g}{2} - \sqrt{\left(\frac{d_g^2}{4} - \frac{F_n}{H_w \pi}\right)} \quad (7)$$

where, F_n is normal force applied to abrasive grain, t is depth of indentation of abrasive into workpiece material, H_w is hardness of workpiece material and d_g is diameter of abrasive grain. Similarly, angle θ can be calculated using the triangle ΔOAB shown in Figure 4(b);

$$\theta = \sin^{-1}\left(\frac{2a}{d_g}\right) \quad (8)$$

The generated cross-sectional area of the groove (A_g) which is the hatched area of the grain in Figure 4(a) is the difference between the areas of sector OADCO and triangle ΔAOC.

$$A_g = \pi \frac{d_g^2}{2}\left(\frac{\theta}{2\pi}\right) - \frac{1}{2} 2a \left(\frac{d_g}{2} - t\right) \quad (9)$$

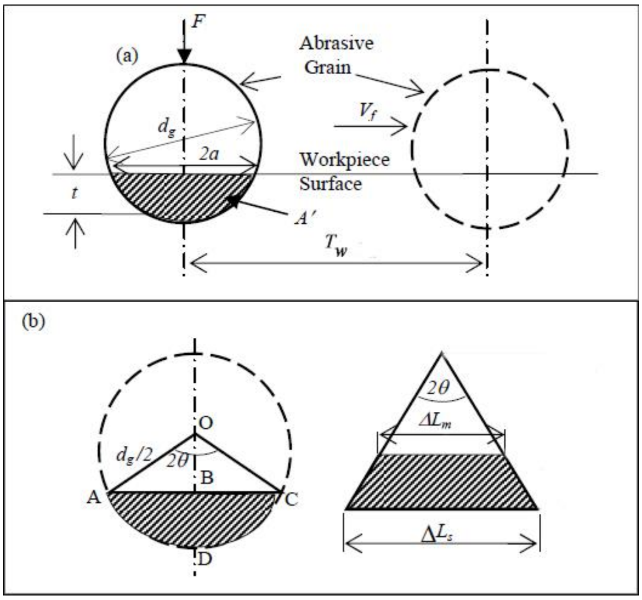

Figure 4. (a) Spherical representation of abrasive grain (b) Triangular asperity model of the workpiece surface [13]

By substituting a and θ from Eqns. (6) and (8), (A_g) is found as;

$$A_g = \frac{d_g^2}{4}\sin^{-1}\frac{2\sqrt{t(d_g-t)}}{d_g} - \sqrt{t\left(d_g - t\right)}\left(\frac{d_g}{2} - t\right) \quad (10)$$

Then the material removed by weight (W_a) by an abrasive grain is;

$$W_a = \rho A_g T_w \quad (11)$$

where T_w is the workpiece width. By substituting A_g into Eqn. (11),

$$W_a = \rho\left[\frac{d_g^2}{4}\sin^{-1}\frac{2\sqrt{t(d_g-t)}}{d_g} - \sqrt{t\left(d_g - t\right)}\left(\frac{d_g}{2} - t\right)\right]T_w \quad (12)$$

Assuming that all active grains behave similarly, the total material removal is the multiplication of the number of active grains (N_a) by W_a. The number of active grains (N_a) per unit length is;

$$N_a = \frac{C}{d_g} \quad (13)$$

where C is the abrasive media concentration by weight. From this, total number of abrasive grains acting to surface of workpiece (N_s) is equal to

$$N_s = SN_aL_m \quad (14)$$

Length of the media (L_m) can be calculated from the rate between areas cylinder and slot cross-section. S is workpiece contour length and Ts is slot thickness of passage which media passes.

$$L_m = \frac{\pi {R_c}^2 L_s}{ST_s} \quad (15)$$

where, L_s is stroke length and R_c is radius of media cylinder. Hence, the weight of material removed in a single stroke (W) of the AFM process is derived as;

$$W = W_aN_s \quad (16)$$

Total weight of material removal (Wt) can be found by multiplying the number of cycles (n)

$$W_t = nW \quad (17)$$

$$W_t = n \times \rho\left[\frac{d_g^2}{4}\sin^{-1}\frac{2\sqrt{t(d_g-t)}}{d_g} - \sqrt{t\left(d_g - t\right)}\left(\frac{d_g}{2} - t\right)\right]T_w \times SN_aL_m \quad (18)$$

According to this model, the material removal depends on the indentation depth (t), the abrasive grains size (dg), and the number of abrasive grains (Ns) acting on the working area of the workpiece.

2.3. The CFD Model

ANSYS FLUENT was used for analyzing the process. By using the results of the analysis the wall shear stress, velocity distribution, and static and dynamic pressure values can be determined and used in the mathematical model. The workpiece model has a rectangular flow passage (2mmx20mmx10mm) as shown in Figure 5.

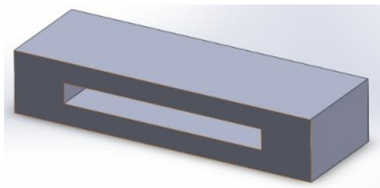

Figure 5. Workpiece mode

Figure 6. Two-way abrasive flow machine

3. Experimental Study

The experimental study was performed on a two-way AFM machine which was shown in Figure 6. The Ti-6Al-4V alloy samples were cut by using wire-EDM to 5x10x20 mm prisms from a stock (Figure 7). The samples were weighed by using

Shimadzu Aux220 balance before and after the AFM process. A polymer-based abrasive media was prepared using 400 mesh sizes of SiC abrasives with weight concentrations of 20%, 40%, and 60%. The media and the process parameters were given in Table 1.

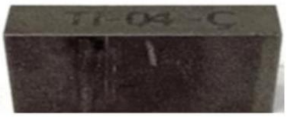

Figure 7. Ti-6Al-4V alloy samples

4. Results and Discussion

The CFD analysis was carried out by using ANSYS FLUENT and the results were shown in Figure 8. The wall shear stress is 0.517 MPa for the flow geometry. The material removal caried out using 400 mesh size SiC abrasive for abrasive concentrations of 20%, 40%, and 60% by weight. The results of the experimental study were compared with the results of the mathematical model presented in this study. The comparison of the mathematical and experimental material removal can be seen in Figure 9 for various AFM cycles.

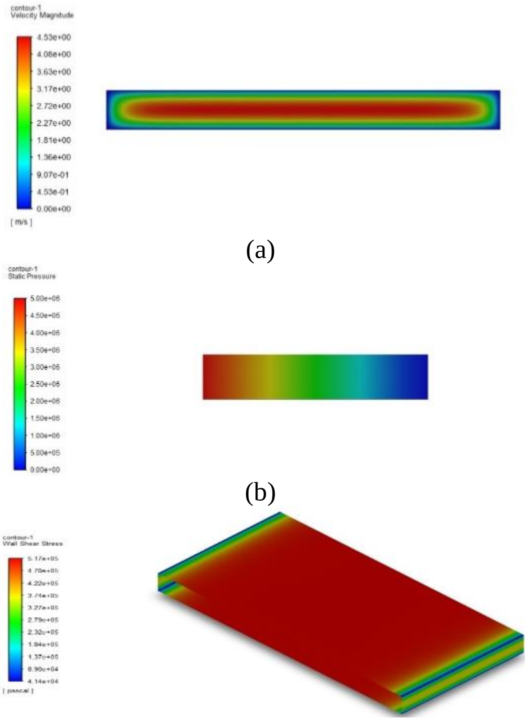

Figure 8. The results of CFD analysis a) velocity b) static pressure and c) wall shear stress distributions.

The amount of material removal is increasing with the increasing abrasive concentration. It can be clearly seen in the figures. The difference between the results of the presented model and experimental ones are very close to each other for all abrasive concentrations. With a help of the presented model, material removal can be pre-determined before the AFM process. In the material model; the media viscosity, the workpiece material hardness, the area of the passage, abrasive grain size, and wall shear stress value are the main dependent values that affect the system. Therefore, the model needs to be verified for other parameters (i.e. viscosity of media, the hardness of workpiece material, area of the passage, and abrasive grain size) also.

Table 1. The AFM media and the process parameters

Parameter	Value
Number of cycles	1, 3, 5, 10, 20, 50
Abrasive type	SiC
Abrasive mesh size	400
Abrasive media	Polymer based
Abrasive concentration	20%, 40%, 60 % wt.
Abrasive media speed	400 mm/min
Abrasive media viscosity	60 Pa.s
Abrasive media flow per cycle	6 liters per 90 seconds
Working pressure	5 MPa
Bore diameter of the AFM machine	140 mm
Stroke length of the AFM machine	400 mm

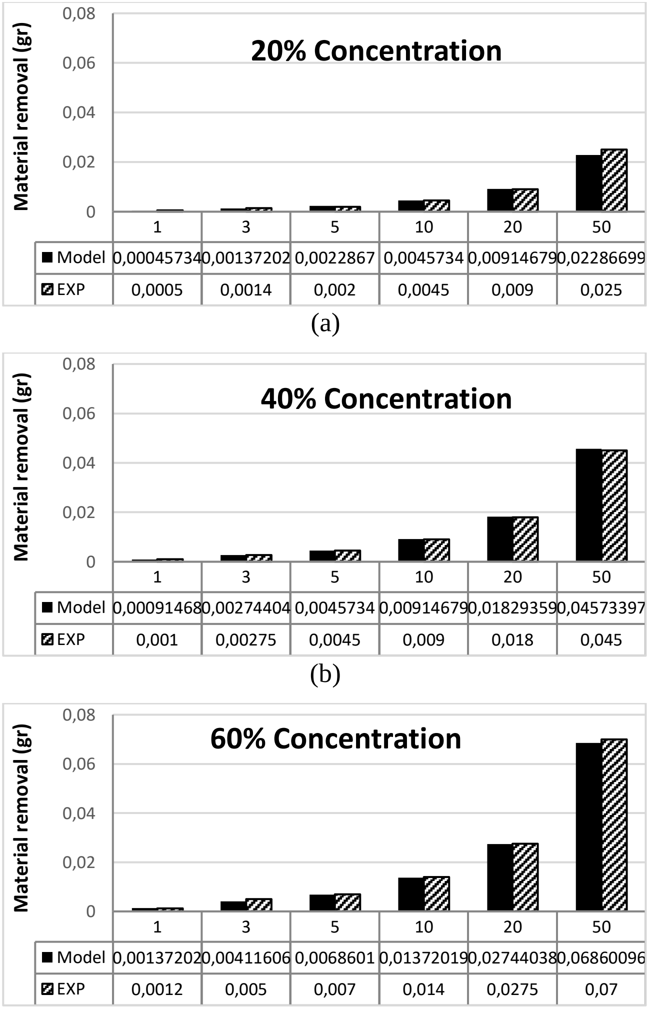

Figure 9. The material removal results predicted by the mathematical model and the experimental study with respect to AFM cycles for a) 20% b) 40% and c) 60% abrasive concentrations.

5. Conclusions

In conclusion, the mathematical model which was derived to obtain material removal can be successfully used for the AFM process design. By using the presented model, the AFM process parameters can be pre-determined according to the required final form. The model was verified for different abrasive concentrations for a constant set of other AFM parameters. The model needs to be verified for other parameters (i.e. viscosity of media, the hardness of workpiece material, area of the passage, abrasive grain size) in further studies.

Acknowledgments

The authors would like to acknowledge the contributions of the Scientific Project Bureau (BAPYB) of The Gaziantep University.

Author contributions

All authors contributed to the study conception and design. Omer Eyercioglu performed the project administration, review and editing. Kursad Gov performed the first draft of the manuscript, validation and analysis. Adem Aksoy performed the material preparation, data collection and visualization. All authors commented on previous versions of the manuscript and read and approved the final manuscript.

References

1. Kumar, S.S., Hiremath, S.S., A review on abrasive flow machining (AFM), Procedia Technology. **2016**, 25:1297-1304
2. Dixit, N., Sharma, V., and Kumar, P., Research trends in abrasive flow machining: A systematic review, Journal of manufacturing Processes. **2021**, 64:1434-1461
3. Rhoades, L., Abrasive flow machining: a case study, Journal of Materials Processing Technology. **1991**, 28(1-2):107-116
4. Jain, R.K., Jain, V.K., and Dixit, P., Modeling of material removal and surface roughness in abrasive flow machining process, International Journal of Machine Tools and Manufacture. **1999**, 39(12):1903-1923
5. Jain, R.K., Jain, V.K., Specific energy and temperature determination in abrasive flow machining process, International Journal of machine tools and manufacture. **2001**, 41(12):1689-1704
6. Jain, V., Adsul, S., Experimental investigations into abrasive flow machining (AFM), International Journal of Machine Tools and Manufacture. **2000**, 40(7):1003-1021
7. Li, J., Zhu, Z., Hu, J., Zhou, Z., Zhang, X., and Zhao, W., Particle collision-based abrasive flow mechanisms in precision machining, The International Journal of Advanced Manufacturing Technology. **2020**, 110:1819-1831
8. Munhoz M.R., Dias, L.G., Breganon, R., Ribeiro, F.S.F., de Souza Gonçalves, J.F., Hashimoto, E.M., and da Silva Júnior, C.E., Analysis of the surface roughness obtained by the abrasive flow machining process using an abrasive paste with oiticica oil, The International Journal of Advanced Manufacturing Technology. **2020**, 106(11-12):5061-5070
9. Eyercioğlu, Ö, Göv, K., and Aksoy, A., Abrasive Flow Machining Of Asymmetric Spur Gear Forging Die, Harran Üniversitesi Mühendislik Dergisi. **2018**, 4(1):12-20
10. Göv, K., Eyercioğlu, Ö., Abrasive Flow Machining of Ti-6Al-4V. in International Science and Technology Conference. of Conference. **2017**
11. Kopač, J., Bahor, M., Interaction of the technological history of a workpiece material and the machining parameters on the desired quality of the surface roughness of a product, Journal of Materials Processing Technology. **1999**, 92:381-387
12. Inagaki, I., Takechi, T., Shirai, Y., and Ariyasu, N., Application and features of titanium for the aerospace industry, Nippon steel & sumitomo metal technical report. **2014**, 106(106):22-27
13. Narutaki, N., Murakoshi, A., Motonishi, S., and Takeyama, H., Study on machining of titanium alloys, CIRP Annals. **1983**, 32(1):65-69
14. Gov, K., Eyercioglu, O., Effects of abrasive types on the surface integrity of abrasive-flow-machined surfaces, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture. **2018**, 232(6):1044-1053
15. Gov, K., Eyercioğlu, Ö., and Çakır, M., Investigation of the Effect of Abrasive Flow Machining (AFM) Parameters on Wire Erosion Cut Die Surface, TMMOB Chamber of Mechanical Engineers Konya Branch VI. Machinery Design and Manufacturing Technologies Congress. **2011**
16. Aksoy, A., Eyercioglu, O., and Gov, K., Abrasive Flow Machining Of Fiber Extrusion Spinneret Holes. in The International Conference of Materials and Engineering Technology (TICMET'19). of Conference. Gaziantep Turkey**2019**
17. Bremerstein, T., Potthoff, A., Michaelis, A., Schmiedel, C., Uhlmann, E., Blug, B., and Amann, T., Wear of abrasive media and its effect on abrasive flow machining results, Wear. **2015**, 342:44-51
18. Sudhakara, D., Suresh, S., and Vinod, B., Experimental study on Abrasive Flow Machining (AFM): new approach for investigation on Nano-SiC in the improvement of material removal and surface finishing, Journal of Bio-and Tribo-Corrosion. **2020**, 6(1):24
19. Jain, V., Ranganatha, C., and Muralidhar, K., Evaluation of rheological properties of medium for AFM process, **2001**,
20. Williams, R.E., Rajurkar, K., Metal removal and surface finish characteristics in abrasive flow machining, Mechanics of Deburring and Surface Finishing Processes. Presented At The Winter Annual Meet. of The American Soc. Mechanical. **1989**, 38:93-106
21. Gedik, E., Kurt, H., Recebli, Z., and Balan, C., Two-dimensional CFD simulation of magnetorheological fluid between two fixed parallel plates applied external magnetic field, Computers & fluids. **2012**, 63:128-134
22. Rajeshwar, G., Kozak, J., and Rajurkar, K.P., Modelling and monitoring and control of abrasive flow machining. in Proc. of NSF Design and Manufacturing system conference. of Conference. **1994**
23. Jain, R.K., Jain, V.K., Simulation of surface generated in abrasive flow machining process, Robotics and Computer-Integrated Manufacturing. **1999**, 15(5):403-412
24. Singh, S., Shan, H., Development of magneto abrasive flow machining process, International Journal of Machine Tools and Manufacture. **2002**, 42(8):953-959
25. Seifu, Y., Kumar, S.S., and Hiremath, S.S., Modeling and simulation: machining of mild steel using indigenously developed abrasive flow machine, Procedia Technology. **2016**, 25:1312-1319
26. Soydan, O., Gov, K., and Eyercioğlu, O., Surface Finishing of Aerospace Materials, El-Cezeri Journal of Science and Engineering. **2020**, 7(2):700-709