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EXPERIMENTAL INVESTIGATION ON ONE-WAY ABRASIVE FLOW MACHINING ON HOT WORK STEEL

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Abstract: Abrasive flow machining (AFM) is a process where a semi-solid abrasive-laden media is forced to flow through the internal passages of a workpiece under pressure. In high-resolution work, increased accuracy and faster smooth surface polishing work with the developed motorized AFM prototype. This research presents the effect of the clearance of specimen tools for surface roughness (Ra) of SKD 61 (AISI H13) hot work steel related to AFM. This research experimented with half-spherical specimens. AFM experiments are performed to identify the improved surface roughness when applied to the polishing specimens. Specimens were prepared by being turned, hardened, and polished with sandpaper from number P180 to P1200 and measured with an original value of Ra compared with the final value of Ra at the end of the process. The experimental prototype uses a unidirectional motor drive system different from previously developed machines. The process parameters are as follows: a pressure (p) of 1, 2, and 3 bar, cycle time (t) of 10, 15, and 20 min., an abrasive particle size (Al_2O_3) of 5.0 µm in Silicon Oil (50 % concentration by weight), hardness of specimens 45±2 HRC, etc. The experimental results show that under these conditions, the average surface roughness of specimens was decreased from an original value of Ra 0.057 to 0.042 µm. The greatest response surface (RSM) was obtained at a pressure of 3 bar and a time of 20 minutes. The result allows for better precision control and further development in industrial applications.

Key words: Abrasive flow machining, AFM, surface roughness, one-way AFM, abrasive flow polishing, response surface method (RSM)

1. INTRODUCTION

Abrasive Flow Machining (AFM) is a new type of precision machining process. It uses a viscoelastic abrasive medium to improve surface finish and remove burrs from the internal passages of the workpiece. This abstract provides an overview of AFM, its working principles, applications, and advantages. AFM involves the flow of semi-solid abrasive media through the internal passages of a workpiece under pressure. The media composed of a viscoelastic polymer mixed with abrasive particles, conforms to the intricate contours of the workpiece, resulting in uniform material removal and improved surface quality. AFM is particularly effective in finishing complex internal geometries that are difficult to reach by conventional machining methods. The process parameters, including pressure, flow rate, and dwell time, can be adjusted to achieve the desired surface finish and meet specific requirements. Advanced control and monitoring systems enable precise control over process variables, ensuring consistency and reproducibility in the machining process.

AFM finds applications in various industries, including aerospace, automotive, medical devices, molds and dies, and precision manufacturing. It is employed for achieving high-quality surface finishes, deburring internal passages, improving aerodynamic performance, enhancing fluid flow characteristics, and optimizing the functionality of critical components. AFM offers several advantages over conventional machining methods for finishing internal surfaces. It can achieve precise control over surface finish, remove burrs and sharp edges, deburr complex shapes, and improve surface quality. It is commonly used in industries such as aerospace, automotive, medical, and mold and die making.

Abrasive Flow Machining (AFM) enables high surface finishes and tight tolerances. It provides an economically acceptable surface finish rate for a broad range of industrial components. A finite element model was developed during the process. (Rajendra K. Jain, et al, 1999) [1]. A mechanism for abrasive wear resulting from slow flows of concentrated hard particle suspensions. Show to lead to contacts with surfaces bounding the flow. Compared to finite element simulations and used to calculate measures of wear efficiency (J.J. Hann, P.S. Steif, 1998) [2].

Study on the effects of parameters of the different processes of AFM such as the number of cycles, the concentration of abrasive, abrasive mesh size, and media flow speed. Study in material removal and surface finish. To find the dominant parameters such as medium percentage concentration, abrasive media mesh size, surface roughness, number of cycles or cycle time or machining time, mathematical modeling, material removal, surface finish improvement (delta (Δ) Ra), and speed of media flow. Test with Brass and Aluminum by comparing experimental and theoretical workpiece surface with Scanning electron microscopy: SEM, experiment on Lath by setup on turret steady rests (V.K. Jain, and S.G. Adsul, 2000) [3].

Simulation of surface generated in AFM process, parametric analysis (Rajendra Kumar Jain, Vijay Kumar Jain, 1999 [4]. A neural network with four inputs, two outputs, and one hidden layer was used to model the process. The second network, parallelizing the Lagrange multiplier algorithm (ALM), determines the optimal machining parameters by minimizing the performance index based on appropriate operating constraints. (Rajendra Kumar Jain, Vijay Kumar Jain, 2000 [5].

Results of experimental studies (Mixed factorial design) were conducted to understand the material removal (MR) mechanism and wear behavior of certain materials when processed by AFM and magnetic-assisted flow machining (MAAFM). Great impact on MR in AFM (Shijpal Singh, et. al., 2002) [6], [15]. Deburring of burrs in spring collects by AFM that occurring inside the small and large diameters. In this study, spring collects made of chrome-molybdenum were used to test (Jeong-Du Kim, Kyung-Duk Kim, 2004) [7]. Optimization of the Magnetic abrasive finishing process of SS304 RSM was applied to optimize the process parameters (Jagdeep Singh Gill, Lakhvir Singh [29].

Development of AFM variants that show in the schematic of (a) One-way AFM, (b) Two-way AFM, (c) Multi-way AFM, and (d) Orbital AFM (Nitin Dixit, Varun Sharma, Pradeep Kumar, 2021) [8].

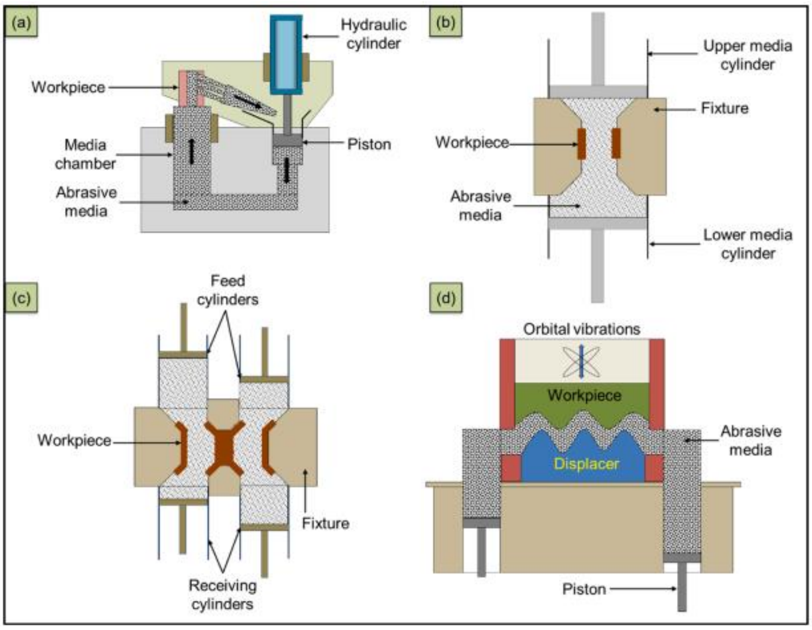


Fig. 1. Schematic of (a) One-way AFM, (b) Two-way AFM, (c) Multi-way AFM, and (d) Orbital AFM, [8]

Mamilla Ravi Sankar, et. al., 2009 [9], [10], [11] studied R-AFF Al alloy, Al alloy/SiC (10%), and Al alloy/SiC (15%) metal matrix composites (MMC) showed that the workpiece rotation speed had a significant impact on Delta Ra CFD numerical method helps to design a good path to find smooth roughness on complex holes. (A-Cheng WANG, et al., 2009) [12], E. Uhlmann, et al., 2015 [20], [21], [27].

EDM pre-machined hardened tool steel AISI D2 samples were used to experiment. It can induce high compressive residual stresses in a very thin sublayer of ~ 10 µm (J. Kenda, et al., 2011) [13].

Dirk Bahre, et al., 2012 [14] Similar to the experiment of Martin Swat, et al., 2014 [18] This paper presents the results of a parameter study that was used to identify the influence of medium pressure and lead time on the surface quality and form tolerance, AISI 4140 by hydraulic cylinder.

AFM uses the visco-elastic polymeric carrier, combined with abrasive particles, the Generalized Maxwell model (E. Uhlmann, et al., 2013) [16]. Increased viscosity of the abrasive medium and progressive rounding of the abrasive performance. [22], [25].

G. Venkatesh, et al., 2014 [17] study the effects of important parameters, extrusion pressure, abrasive mesh size, processing time, and media flow rate on finishing EN-8 steel bevel gears have been investigated. The initial SR was 1.4 to 1.8 µm, and G. Venkatesh, et al., 2015, used ultrasonic-assisted abrasive flow finishing of bevel gears [19]. A model linking numerically calculated parameters with empirical process parameters has been developed for machined ceramic materials. The results of the project transferring the model to metal materials and the current needs of the automotive industry in hole-cutting fuel rail and feed pipe with a high aspect ratio. (E. Uhlmann, et al., 2016) [23]. The modern manufacturing process used to experiment such as selective laser melting (SLM) M.S. Duval-Chaneac, et al., 2018 [24], [26], [28].

The problem of polishing a surface with a high surface smoothness requires the development of a machine that is precise and convenient to polish the surface of the workpiece. To rely on knowledge and skills in creating and developing such machines. The application of industrial pumps is different from previous research. To find the most suitable results, the researchers chose to study a unidirectional abrasive flow machine where the abrasive substance consists of aluminum oxide mixed with silicone oil and analyzed. To study the effect of the clearance of specimen tools for surface roughness (Ra) of SKD 61 (AISI H13) hot work steel. Results using RSM statistical principles to achieve the research objective, which is the desired surface roughness according to the work design.

2. MATERIALS AND METHODS

2.1. Experimental set-up

Experimental setup of a unidirectional prototype. As shown in Figure 2, it has been designed and developed to be able to store abrasive substances in a circulating manner to create pressure to flow and polish the surface of the workpiece so that it can work continuously in polishing the workpiece. The workpiece chuck is designed to be replaceable according to the workpiece type, making it convenient. The driven pump is food grade, brand NETZSCH.

(a) (b) (c)

(d) (e) (f)

Fig. 2. Display (a) One-way AFM prototype, (b) workpiece holder (c) flow of abrasive media (d) nameplate of motor, (e) inverter control, (f) pressure display

2.2. Workpiece and medium

Experiment with abrasives containing Aluminum Oxide (Al_2O_3) and Silicon oil ingredients with a concentration of 50% by weight to experiment with hardened SKD61 workpieces 45±2 HRC.

Fig. 3 SKD61 (AISI H13) Workpiece of AFM prototype

2.3. Experimental procedure

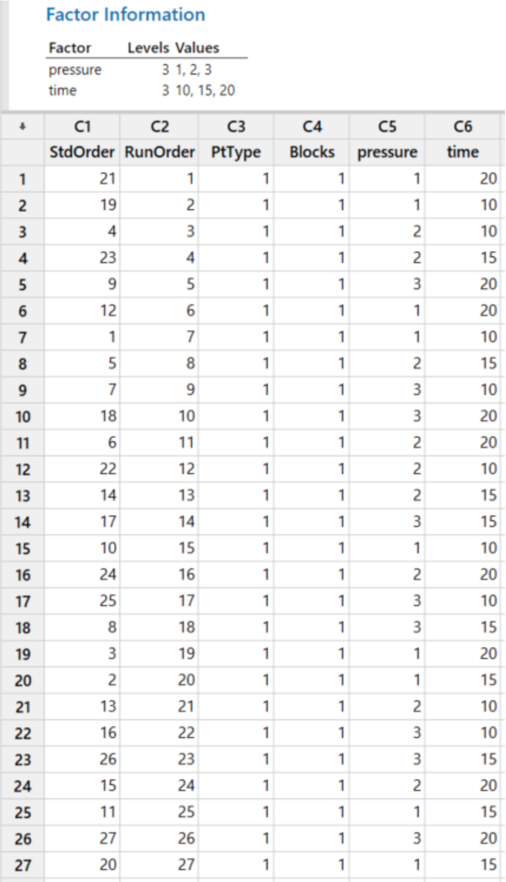
Experimental procedure for unidirectional polishing machines It consists of setting objectives. Identification of factors and factor levels before experimenting the details are as follows:

1.Set the objective: I was trying to adjust the surface appropriately.

2.Identify factors: Choose two important factors to study. These can be pressure and cycle time.

3. Set level factors: Set levels for each factor. Select 3 pressure levels (1, 2, and 3 bar) and cycle times 10, 15, vand 20 minutes.

4. Experimental design: A factorial experimental design was used to combine levels. of the two factors together systematically for a full factorial design Test all possible combinations of factor levels. Shown in Figure 4.



Factor Information

Factor	Levels	Values
pressure	3	1, 2, 3
time	3	10, 15, 20

↓	C1	C2	C3	C4	C5	C6
	StdOrder	RunOrder	PtType	Blocks	pressure	time
1	21	1	1	1	1	20
2	19	2	1	1	1	10
3	4	3	1	1	2	10
4	23	4	1	1	2	15
5	9	5	1	1	3	20
6	12	6	1	1	1	20
7	1	7	1	1	1	10
8	5	8	1	1	2	15
9	7	9	1	1	3	10
10	18	10	1	1	3	20
11	6	11	1	1	2	20
12	22	12	1	1	2	10
13	14	13	1	1	2	15
14	17	14	1	1	3	15
15	10	15	1	1	1	10
16	24	16	1	1	2	20
17	25	17	1	1	3	10
18	8	18	1	1	3	15
19	3	19	1	1	1	20
20	2	20	1	1	1	15
21	13	21	1	1	2	10
22	16	22	1	1	3	10
23	26	23	1	1	3	15
24	15	24	1	1	2	20
25	11	25	1	1	1	15
26	27	26	1	1	3	20
27	20	27	1	1	1	15

Fig. 4. The experimental plan (DOE: Design of Experiment)

5. Conduct the experiment: An AFM experiment is performed for each combination of factor levels. Ensure that experiments are conducted under controlled and consistent conditions. The workpiece surface was prepared with sandpaper ranging from P180 to P1200 to measure the initial surface roughness (SR) of the micron before the AFM process. Polishing was performed with the AFM prototype within 10, 15, and 20 min, respectively.

6. Data collection: Measure and record the response of interest after each trial by the MarSurf PS1 and 2D profile; Keyence VR-6000 Series 2D (profile measurement only) (see Figure 5). This may involve measuring the amount

of surface roughness. To evaluate other performance indicators. It is related to measuring the surface roughness after polishing using AFM (Final SR) to measure the raw and modified profiles of the workpiece.


(a) (b)

Fig. 5. The surface measurement: (a) Mahr; MarSurf PS1, (b) Keyence VR-6000 Series

7. Statistical analysis: Use statistical methods such as analysis of variance (ANOVA) to analyze data by Minitab 19. This helps identify important main effects and interactions between the two factors. Statistics plays an important role in the analysis and interpretation of AFM-related data through the use of statistical methods. Researchers can gain insights into the performance, variability, and optimization of the AFM process. Response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response.
8. Validation: Verify your findings by performing additional experiments or using a separate dataset. This ensures the reliability and generalizability of the results.
9. Interpretation and conclusions: Interpret results in the context of the objectives. Results are summarized regarding the impact of selected factors on the AFM process.
10. Documentation and Reporting: Record experimental setup, procedures, and detailed results. Prepare a summary report or presentation summarizing the research results.

3. RESULTS AND DISCUSSION

Results from the experiment according to the experimental design, which shows the relationship with the pressure and time parameters for easier viewing, are summarized in Table 1. The results of the experiment follow:

3.1. Statistical Analysis

Design of Experiments (DOE) is a systematic approach used to optimize process parameters in AFM. By conducting a DOE, researchers can identify the optimal combination of factors that will yield the desired surface finish, material removal rates, or other performance measures.

Table 1. Results pressure 1, 2, 3 bars; cycle time 0 to 10, 15, and 20 minutes, 3 duplicate

	1 bar		2 bar		3 bar
Time	Δ SR (Ra, μm)		Δ SR (Ra, μm)		Δ SR (Ra, μm)
10	0.006		0.008		0.010
	0.007		0.003		0.006
	0.008		0.008		0.009
15	0.007		0.009		0.011
	0.009		0.010		0.011
	0.009		0.011		0.010
20	0.008		0.011		0.013
	0.010		0.009		0.012
	0.012		0.010		0.011

Table 1 displays the relationship between surface roughness, (μm) and polishing with AFM prototype at 1, 2, and 3 bars and cycle time from 0 to 10, 15, and 20 minutes consequently.

Measure the surface roughness first, and after the experiment display the surface profile of the workpiece with a measuring device. The top surface was less different than before the experiment. The results from an experiment to determine surface roughness with a PS1 surface roughness tester. The surface profile was measured with a Keyence VR-6000 series an example shown in Figure 6.

Analysis condition

2D coordinate settings	None
Measurement type	Roughness
Cutoff	λs =None λc =0.8mm
End effect correction	Enabled
Double gaussian	OFF
Stylus mode	OFF
No. of sampling lengths	4

Measurement result

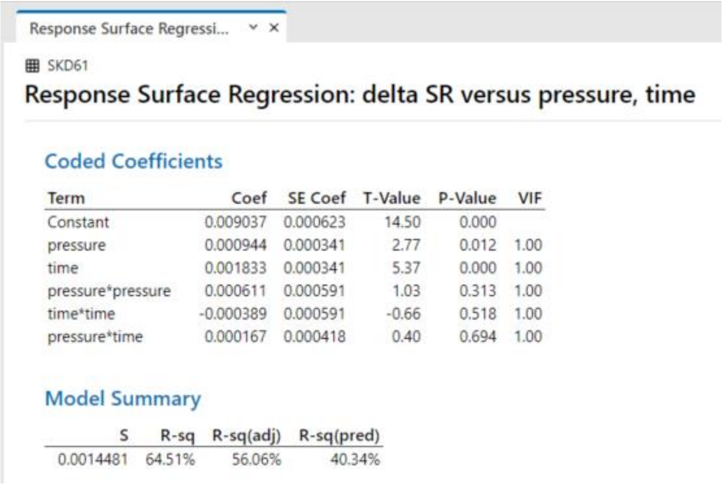
No.	Measurement name	Measured value	Unit
1	Ra	1.151	µm
2	Rz		µm

Fig. 6. Shows surface roughness polishing with the AFM prototype

Figure 6 The surface roughness in 2D (line/Profile Measurement, not Area Measurement) and Ra (micron) with AFM prototype at 1, 2, and 3 bars.

3.2. Response Surface Methodology

The RSM was followed: ANOVA table: If the P-value of any factor is less than the significance level of 0.05, then that factor has a significant effect on the results. Delta SR versus pressure, time.



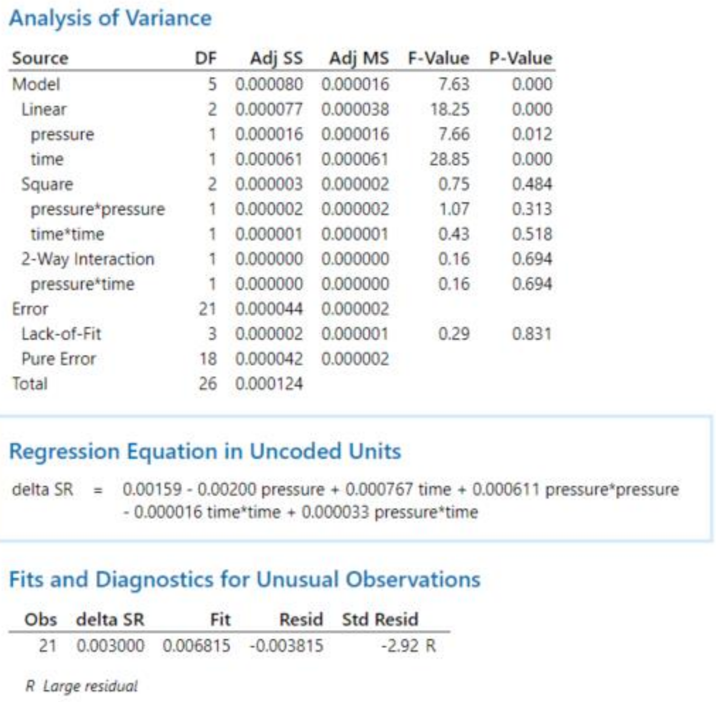
Response Surface Regression: delta SR versus pressure, time

Coded Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0.009037	0.000623	14.50	0.000	
pressure	0.000944	0.000341	2.77	0.012	1.00
time	0.001833	0.000341	5.37	0.000	1.00
pressure*pressure	0.000611	0.000591	1.03	0.313	1.00
time*time	-0.000389	0.000591	-0.66	0.518	1.00
pressure*time	0.000167	0.000418	0.40	0.694	1.00

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.0014481	64.51%	56.06%	40.34%



Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	0.000080	0.000016	7.63	0.000
Linear	2	0.000077	0.000038	18.25	0.000
pressure	1	0.000016	0.000016	7.66	0.012
time	1	0.000061	0.000061	28.85	0.000
Square	2	0.000003	0.000002	0.75	0.484
pressure*pressure	1	0.000002	0.000002	1.07	0.313
time*time	1	0.000001	0.000001	0.43	0.518
2-Way Interaction	1	0.000000	0.000000	0.16	0.694
pressure*time	1	0.000000	0.000000	0.16	0.694
Error	21	0.000044	0.000002		
Lack-of-Fit	3	0.000002	0.000001	0.29	0.831
Pure Error	18	0.000042	0.000002		
Total	26	0.000124			

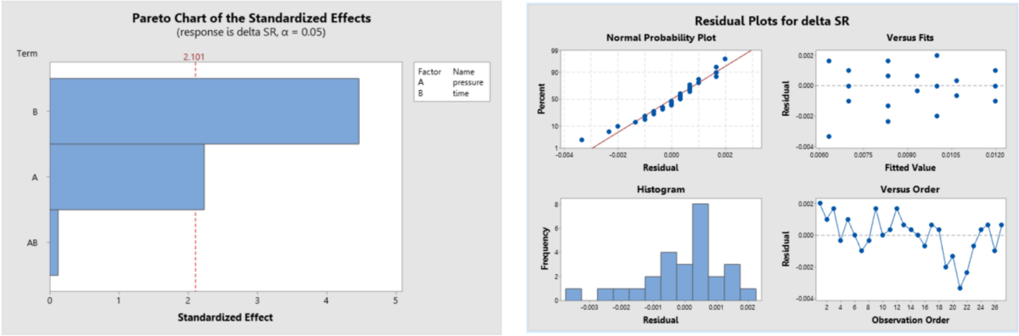
Regression Equation in Uncoded Units

delta SR = 0.00159 - 0.00200 pressure + 0.000767 time + 0.000611 pressure*pressure - 0.000016 time*time + 0.000033 pressure*time

Fits and Diagnostics for Unusual Observations

Obs	delta SR	Fit	Resid	Std Resid
21	0.003000	0.006815	-0.003815	-2.92 R

R Large residual



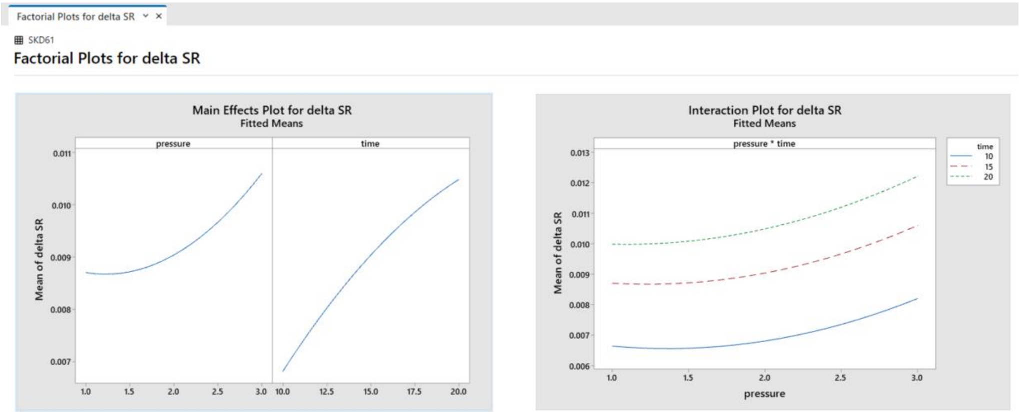
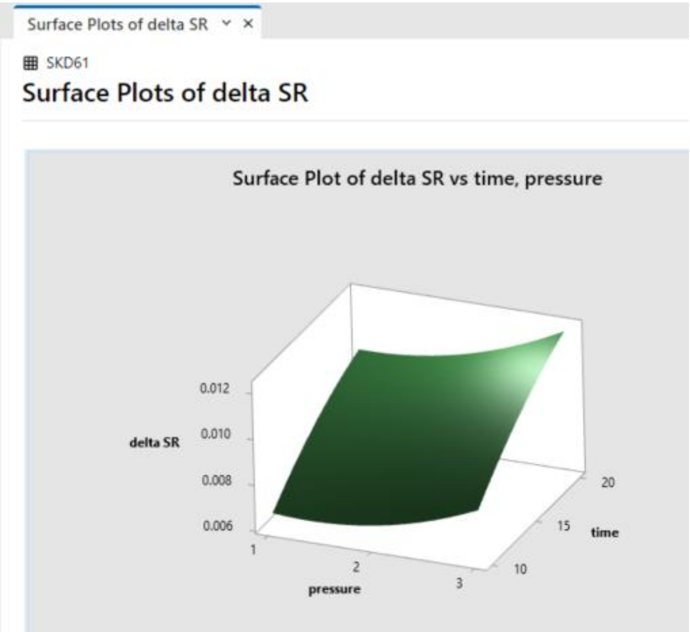


Fig. 7. Response Surface Regression: Coded Coefficients, Model Summary, ANOVA, Regression Equation, and Fits and Diagnostics

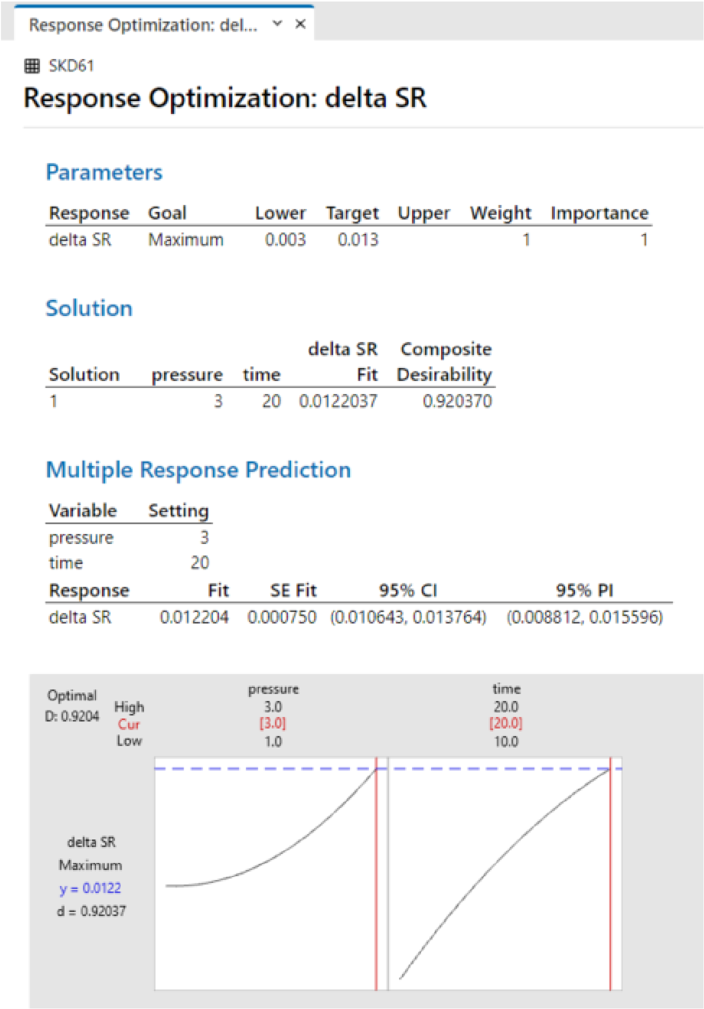
P-value or probability value is a value used in statistical hypothesis testing. It indicates the significance level or probability of an observed effect. or results that differ from what was expected under the assumption of no effect. (main hypothesis). A P-value less than 0.05 indicates that the factor equation has a significant effect on the experimental response. The P-value of the quadratic term or the resulting quadratic equation. If the P-value is less than 0.05, then the equation factor has a significant impact on the response. A P-value greater than 0.05 indicates that the calculated relationship equation is accurate (Equation delta SR). If the P-value is less than 0.05, the relationship equation may have a high error range -- correlation coefficient (r^2) with R-Sq equal to 64.51%. Relationship equation of factors and responses error analysis Check the normal distribution of the error values.

The data has a normal distribution of error values. The error variance is uniform. Independence is a characteristic of a good control plan.



Surface Plots of delta SR

Fig. 8 Surface Plots of delta SR.



Response Optimization: delta SR

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
delta SR	Maximum	0.003	0.013		1	1

Solution

Solution	pressure	time	delta SR Fit	Composite Desirability
1	3	20	0.0122037	0.920370

Multiple Response Prediction

Variable	Setting
pressure	3
time	20

Response	Fit	SE Fit	95% CI	95% PI
delta SR	0.012204	0.000750	(0.010643, 0.013764)	(0.008812, 0.015596)

Fig. 9. Response Optimization: delta SR; Solution, and Multiple Response Prediction

The value of the factor required for setting to get the highest response value. Variable A pressure (p) 3.0 bar Variable B cycle time (t) 20 minutes. Which has a direct interaction with the dominant pressure and time. The desired response value is 0.012. Confidence interval is that if the experiment is repeated and averaged, it will be found that the chance of getting the average response in this range is approximately 95%. The prediction range is that if the same experiment is repeated, it will be found that the chance of getting the response value in this range is approximately 95%. The rising time trend is an increasing curve.

4. CONCLUSIONS

In conclusion, we have introduced a prototype industrial pump motorized one-way polishing flow in hot work molding for precise and convenient control to reach the target according to the specified design. The experiment of workpiece polishing SKD61 Hot Work Steel. The result is that pressure 1, 2, 3 bar consequently and cycle time range 10, 15, and 20 minutes, an abrasive particle size (Al_2O_3) of 5.0 µm in Silicon Oil (50 % concentration by weight), hardness of specimens 45±2 HRC by following:

The value of before and after of average surface roughness middle and trend to decrease surface roughness value (Ra) from 0.057 to 0.042 µm.

Pressure 1 bar; the difference before and after of average SR, 0.057 to 0.044 µm trend to decrease. The difference; is delta 0.006 to 0.012 µm

Pressure 2 bar; the difference before and after of average SR, 0.058 to 0.043 µm trend to decrease. The difference; is delta 0.008 to 0.011 µm

Pressure 3 bar; the difference before and after of average SR, 0.057 to 0.042 µm trend to decrease. The difference; is delta 0.006 to 0.013 µm

- The value of before and after of average surface roughness middle and trend to decrease surface roughness value (Ra) from 0.057 to 0.042 µm. More pressure will affect the surface roughness able to produce a difference in surface roughness that is greater as a result, a smooth surface can be obtained faster and closer to the required surface roughness SR.
- The greatest response surface maximum (RSM) was applied to develop a model and optimize the process parameters. It is obtained for a pressure of 3 bar and a cycle time of 20 s, The desired response value is 0.012204 which has a direct interaction with the dominant pressure and time, respectively.

The AFM results demonstrate its effectiveness in achieving a high-quality surface finish. Removes burrs and sharp edges and improves the overall surface integrity of the workpiece in terms of surface quality and machining efficiency achieved. The research examines the effectiveness of one-way motorized AFM prototyping. The experimental prototype uses a unidirectional motor drive system different from previously developed machines. Work will be developed to be more accurate by using Machine learning and AI techniques to control work with Labview to help control accuracy and convenience faster and create widespread industrial use.

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Conflicts of Interest: There is no conflict of interest.

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