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3D Surface Characterization of Electrophoretic Deposition Assisted Polishing of SS316L

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Abstract: Electrophoretic deposition assisted polishing process (EPDAP) is a recently developed polishing process known to achieve nano finished surfaces. Literature reveals that very few studies have been conducted to analyze the electrophoretic deposition assisted polishing process. In this experiment, quantitative as well as qualitative assessment of surface characteristics obtained by EPDAP process of SS316L. The polishing tool with homogeneously organized and, uniformly dispersed micro abrasive grains by electrophoretic deposition (EPD) was employed in this process. The experiments were conducted using statistical full factorial design (2^4) approach. The control parameters selected for were grit size, axial load, rotational speed and polishing time. Abrasive grains with blunt edges are easily ablated from the polishing tool by friction during EPDAP. Therefore polishing wheel was continuously refreshed by adding new abrasives. The experimental results are analyzed using ANOVA. The significant improvement in surface reflection after EPDAP process was observed. The optimum polishing performance for the surface finish was obtained at the grit size 2000, axial load of 12 N, rotational speed of 1500 rpm and polishing time of 10 min. This is the optimum parameter setting obtained under the conditions in which experiments was performed. The experimental result shows the surface roughness up to 0.04557 microns could be achieved in this investigation. Whose surface roughness before electrophoretic deposition assisted polishing was 0.75 microns. Thus a significant improvement in percentage in reduction surface roughness was 93.92% achieved.

Key words: Electrophoretic deposition assisted polishing process, SS316L, SiC, pH, ANOVA

INTRODUCTION

Final finishing operations in manufacturing of precise parts are always of concern owing to their most critical, labor intensive and least controllable nature. In era of nanotechnology, a deterministic high precision finishing method is of utmost importance and is prime need of present manufacturing scenario. The need of high precision in manufacturing was felt by manufacturers worldwide to improve interchangeability of components, improve quality control and longer wear/fatigue life. We require extremely smooth surface at the mating faces of moving parts having relative motion between them. These smooth surfaces help to reduce friction it is not the only application related to engineering field (Mckewon, 1987). Polishing process is one of the main secondary manufacturing processes and its purpose is to reduce the surface roughness to a desired amount. Industrial applications of the polishing process span from large products such as automobile, aerospace, to small parts such as optics (Xi and Zhou, 2005). Electrophoresis is the motion of charged particles in suspension under the influence of an electric field. Deposition is the coagulation of particles to dnese mass, when an electromagnetic field is applied, the abrasives are attracted to an anode and deposit on it. We call this phenomenon "electrophoretic deposition (EPD)" (Ikeno *et al*., 1994). Electrophoretic deposition (EPD) is a powerful method for the production of coatings and both thin and thick films. Oxide particles usually have some electrical charge in water. In EPD, charged particles migrate to an electrode of opposite charge under the influence of a dc electrical field. The suspension must have a high stability which can be achieved electrostatically or by adding charged polymers or surfactants (Ikeno *et al*., 1991).

Though the electrophoresis is well known phenomenon for the other processes but its application to achieve for the mirror finish surfaces has been initiated in the early nineties. Till date, very few authors have conducted experimental research for producing optically smooth surfaces and ultrafine finish surfaces using the electrophoretic deposition principle. There is considerably insufficient literature available in the area of polishing of stainless steel using electrophoresis deposition technique. Moreover, the effect of process conditions on the polishing mechanism is not fully understood. Also the

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correlation between process parameters and the surface characteristics has hardly been reported. EPD is a combination of two processes: electrophoresis and deposition.

There are only few articles that can be found from prior literature review utilizing electrophoretic deposition assisted polishing process. Takahata *et al.* (1996) used this technique to polish 3-dimensional micro components in MEMS sing 100 microns alumina abrasives. Ikeno *et al.* (1991) introduced chipping free dicing technology for silicon wafer, lime glass, lithium-niobate and Mn-Zn ferrite applying electrophoretic deposition of ultra fine abrasive. They developed highly homogeneous palettes for electrophoretic deposition of ultra-fine abrasives. Tani *et al.* (1998) employed infeed grinding of silicon wafers applying electrophoretic deposition of ultrafine abrasives for grinding wheels which produce a mirror surface finish (R_t) of 23 nm. Yan *et al.* (2007) introduced micro energy EDM followed by EPD polishing of SKD 61 Die steel. They compared polished surface generated by micro energy EDM and EPD polishing. A better surface qualities within short period of time was observed using EPD polishing. Tusi *et al.* (2007) studied the electrophoretic deposition of SiC particles to polish stainless steel. They found improvement in surface finish (R_a) from 0.5-0.02 µm in 8 min with mirror like surface.

MATERIALS AND METHODS

Design of experiments: Design of Experiment (DoE) is an efficient experiment planning process that allows the data obtained to be analyzed, valid conclusions to be drawn and objectives to be set. DoE is used to determine the appropriate number of tests and the experimental conditions necessary to obtain desired goal of analyzing which factors of the process influence the response variable. The most common design consist of running the test with all possible combinations of variables at each of two levels, thereby obtaining most information required of multilevel experiment. The experiments were planned to find optimum polishing performance of EPDAP on SS316L. These are planned according to full factorial design array (2^k where k = 4). For this, four parameters each of them with tow levels are selected. Hence, the total of 2^4 experiments, total no of experiments is (Montgomery, 1997).

Selection of process parameters and their levels for optimizing results: The process parameters selected for this experimental investigation are-grit size, axial load, rotational speed and the polishing time. The levels of process parameters were selected from past literature and their values are shown in the Table 1. Table 1 shows variable parameter and their levels and Table 2 shows fixed parameter of EPDAP. The standard run order of full factorial method 2^k (where k = 4, i.e., number of parameters) is shown in Table 3.

Table 1: Control parameters and their levels

Control parameter	Symbol	Levels I	Levels II
Grit size	D_a	1500	2000
Axial load (N)	L	12	20
Rotational speed (RPM)	N	800	1500
Polishing time (min)	T	10	15

Table 2: Fixed parameters used in EPDAP

Fixed parameter	Description
Polishing tool (electrode)	Cu (Ø21 mm)
Specimen	SS316L (Ø20 mm)
Voltage supply	20 V
Solution	Pure water (1.2 L)
Additive	Sodium hydroxide
pH value	9

Table 3: Standard run order for full factorial-2^4

Grit size	Axial load (N)	Rotational speed (RPM)	Polishing time (min)
1	1	0	1
0	1	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	1	0	0
1	1	1	0
0	1	0	1
0	0	0	1
1	0	0	0
0	0	1	1
1	0	1	1
0	0	1	0
0	0	0	0
1	1	1	1
1	0	1	0

Work material: The electrophoretic deposition assisted polishing process is used to polish metals using electrolyte solution containing distilled water, NaOH and abrasive particles. The best results of polishing are obtained with metals with fine grain boundaries that are free of non metallic inclusions and seams. The metals having a high content of silicon, lead or sulphur are usually troublesome. Stainless steels are more frequently polished alloys. The type SS316L steel was used for experiment purpose (Table 4). This type of steel widely used in applications requiring corrosion resistance superior to type 304.

Tooling: Polishing tool for the experiment is fabricated from copper material. One end of the tool is held fixed on the collet of CNC milling machine spindle. On the other end, a non woven fabric is pasted using electrically conductive glue which is used as polishing head. A nylon cap is placed on the collet end of the tool which acts as a barrier for preventing current flow into machine as shown in Fig. 1.

Experimental set up: The EPD polishing system was established by using CNC Milling Machine. Figure 2 shows the experimental set up designed for process under investigation. It has an integral fixture which facilitates quick change of work piece. The electrolyte tank made of acrylic sheets as the material is chemically inert and does not react with any of the possible electrolyte solution which may be used. The anode is made of copper. On this anode, non woven polyester fibers are pasted with electrically conductive glue.

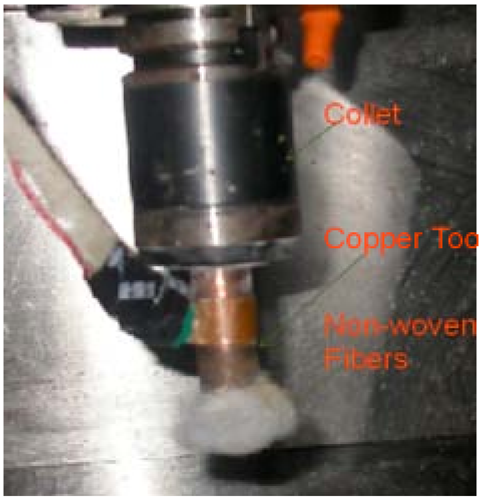


Fig. 1: Photograph of EPDAP polishing tool

Table 4: Chemical analysis of SS316L

Elements (%)	Specified	Observed
C	0.030 max.	0.0220
Mn	2.00 max.	1.7400
Si	1.00 max.	0.4500
S	0.030 max.	0.0094
P	0.045 max.	0.0390
Cr	16-18	17.7000
Ni	10-14	11.2400
Mo	2-3	2.1300

Experimental procedure: Table 5 shows the experimental parameters combination used for conducting the experiments and the values of the response variables obtained for surface roughness and MRR. Figure 3 presents a flow chart that deficit the procedure followed during experiments. The first step is to remove the surface contaminants from the test specimens by degreasing and cleaning. After cleaning, measurements of all specimens were made to obtain surface roughness value using surface roughness tester. The surface roughness R_a, R_z,

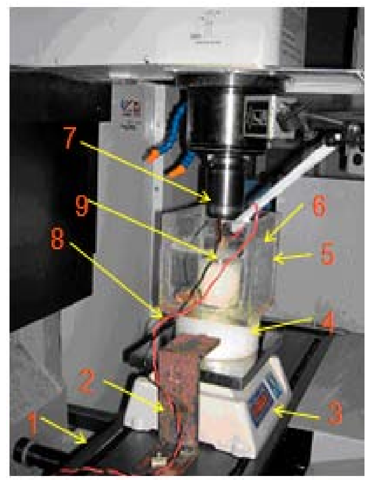


Fig. 2: Experimental set up, (1) Machine table, (2) Clamp (3) Electronic balance (4) Base (5) Electrolyte tank (6) Electrolyte (7) Polishing tool (8) Voltage supply and (9) Work piece

Table 5: Response values for surface roughness and MRR along with the experimental parameter combinations

Grit size	Axial load (L)	Rotational speed (S)	Polishing time (t)	R_a EPDAP Before	R_a EPDAP After	3D-R_a EPDAP Before	3D-R_a EPDAP After
2000	20	800	15	0.42	0.09	0.08146	3.533330
1500	20	1500	15	0.38	0.07	0.07138	4.200000
1500	20	800	10	0.64	0.18	0.09868	3.600000
1500	20	1500	10	0.34	0.08	0.07289	4.010000
2000	12	800	15	0.68	0.07	0.06189	3.126670
2000	20	800	10	0.50	0.12	0.08783	3.140000
2000	20	1500	10	0.60	0.08	0.06078	3.640000
1500	20	800	15	0.67	0.14	0.09517	3.846670
1500	12	800	15	0.86	0.07	0.07081	3.560000
2000	12	800	10	0.47	0.07	0.05983	3.010000
1500	12	1500	15	0.79	0.08	0.06489	3.960000
2000	12	1500	15	0.38	0.06	0.05783	3.620000
1500	12	1500	10	0.59	0.06	0.05476	3.826000
1500	12	800	10	0.31	0.08	0.06700	3.260667
2000	20	1500	15	0.79	0.07	0.06395	3.806670
2000	12	1500	10	0.75	0.05	0.04557	3.530000

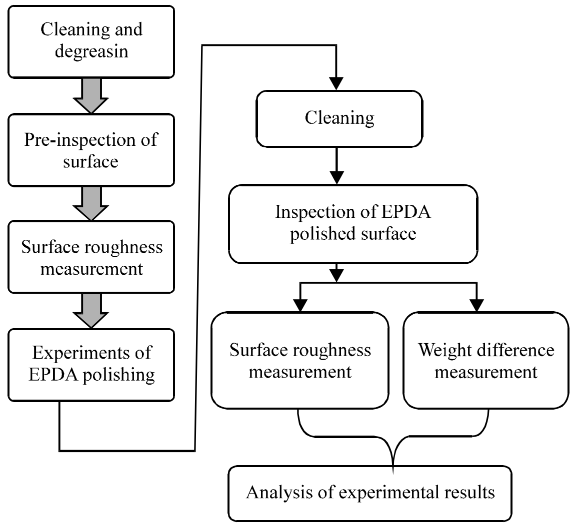


Fig. 3: Flow chart of the EPDAP process

R_q was measured after EPDA polishing. Initially the electrolyte is prepared with the suitable composition described previously. It is continuously stirred using a magnetic stirrer and is ready when pH reaches to 9.

The specimen I placed under the polishing tool and an auxiliary copper electrode is placed near the inner wall of the tank, so that sufficient SiC particles can be deposited on the polishing tool during polishing. Therefore, the end of the polishing tool retains sufficient SiC particles during the polishing of the specimen. The surface roughness of the ground surfaces were measured by stylus based surface roughness tester MITUTOYO SJ-301, Japan. With a resolution of 0.001 μm. and 3-D surface roughness by using Dektak 150 Surface profiler (Veeco) which is available in NCL Pune. The surface roughness parameters considered for the pre finished work piece are R_a, R_z and R_q. A surface roughness was measured for the entire polished specimen at six locations and averaged them to obtain R_a, R_z and R_q values for the specimen.

RESULTS AND DISCUSSION

After carrying out the experiments it is essential now to analyze the data using statistical methods in order to obtain the meaningful conclusion. The experimental data collected during the experiments were analyzed using statistical software. Initial part of this chapter discusses the results of experiment. The effects of four process parameters on the surface roughness and MRR using ANOVA and main effects plot as been discussed.

Table 6: ANOVA table for surface roughness

Source	df	SS	MS	F	p
Regression	4	0.002855	0.000714	21.63	0.000
Residual error	11	0.000363	3.3E-05		
Total	15	0.003218			

Quantitative analysis: Figure 4a-b shows 3-D surface roughness R_a of ground surface and Fig. 4c shows microscope photograph of ground surface at 100X. it is observed that EPDA polished surface shows lower surface roughness R_a = 45.57 nm when the parameter were: abrasive grit size 2000, axial load increases to 12 N, rotational speed increases to 1500 rpm and polishing time of 10 min. was used.

The polishing time dose not significantly influence the surface roughness R_a. Figure 4a-b shows 3-D surface roughness R_a of after EPDAP, Fig. 4c shows microscope photograph after EPDAP at 100X (Grit size = 2000, L = 12 N, S = 1500 rpm, t = 10 min). the higher surface roughness R_a = 98.68 nm, is obtained when the parameter were set as; grit size 1500, axial load increases to 20 N, rotational speed increases to 800 rpm and polishing time 10 min.

Figure 5a-b shows 3-D surface roughness R_a of after EPDAP and Fig. 5c shows microscope photograph after EPDAP at 100X (grit size = 1500, L = 20 N, S = 800 rpm, t = 10 min).

Qualitative analysis: Surface reflectivity can be quantitatively assessed. However, quantitative measurement of surface reflectivity could not be obtained due to lack of facility. But the surface reflection can be observed qualitatively using reflection of letters through visual observation.

After polishing of the work piece it is seen that there is a significant increase in the reflection of letters. This could be due to removed surface irregularities and improved surface finish during electrophoretic deposition assisted polishing (Fig. 6).

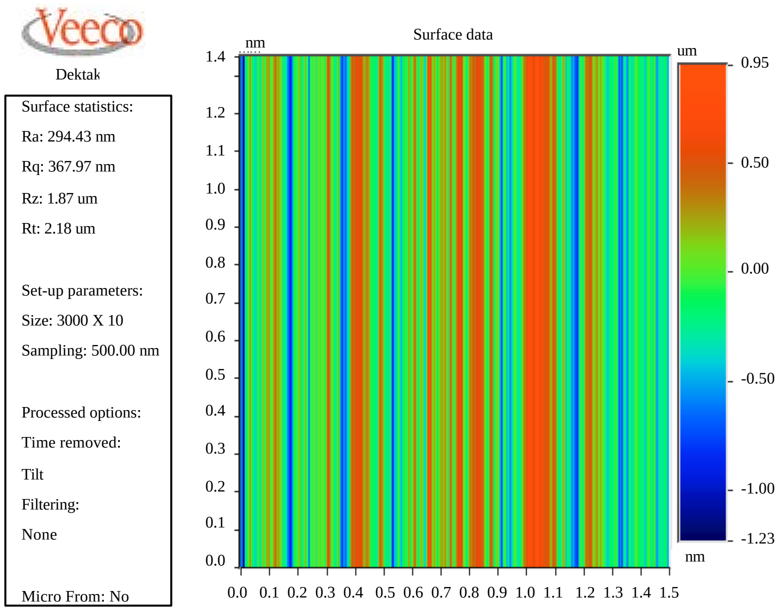
ANOVA for surface roughness: The Table 6 Shows ANOVA summary table of arithmetic average surface roughness R_a.

Regression analysis for R_a: The equation 1 describes the relationship between response arithmetic average surface roughness R_a and predictor variables grit size, axial load (L), rotational speed (S) and polishing time (t).

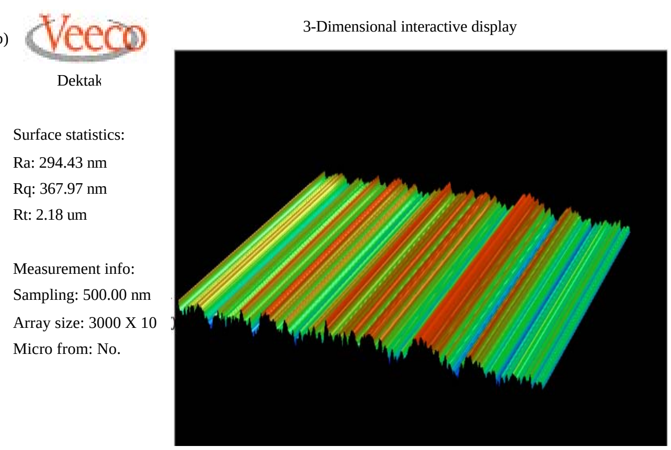
The regression equation is:

$$R_a = 0.0863-0.00019\text{ grit size}+0.00234\text{ L}-0.000023\text{ S}+0.000501\text{ t} \quad (1)$$

(a)



(b)



(c)

Fig. 4(a-b): (a-b) 3-D surface roughness R_a of ground surface and (c) Electron microscope photograph at 100X of ground surface

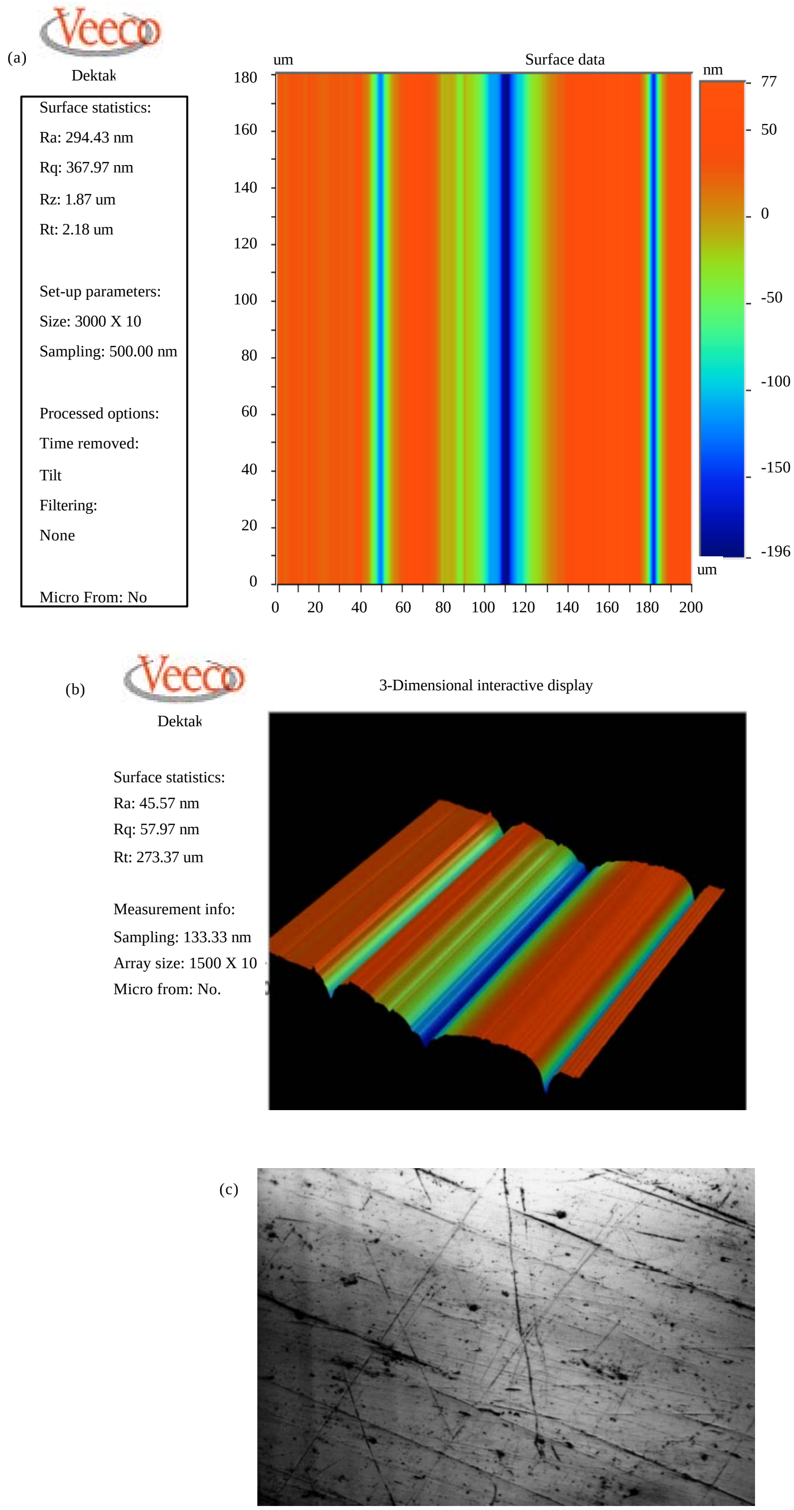


Fig. 5(a-b): (a-b) 3-D surface roughness R_a after EPDAP (c) Electron Microscope photograph at 100X of EPDAP surface

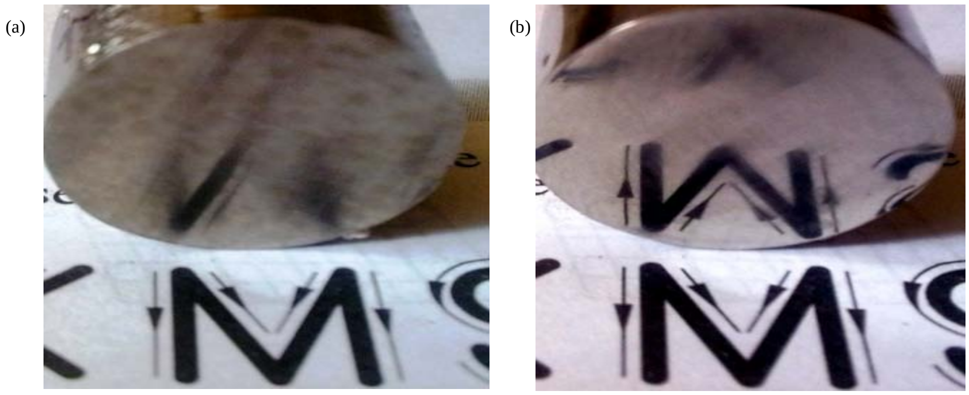


Fig. 6(a-b): Reflection photographs of work piece (a) Before and (b) After electrophoretic deposition assisted (EPDA) polishing

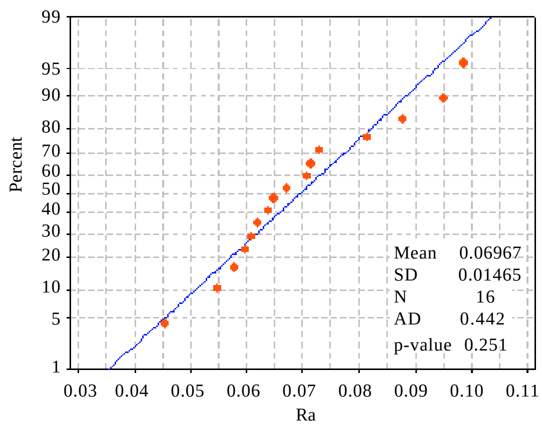


Fig. 7: Normal probability plot of the residuals for response Ra

Table 7: Regression coefficient table for surface roughness

Predictor	Coef.	SE	T	p
Constant	0.08628	0.01449	5.96	0.000*
Grit size	-0.00001911	5.74E-06	-3.33	0.007*
Axial load (N)	0.0023369	0.000359	6.51	0.000*
Rotational speed (rpm)	-0.0000233	4.1E-06	5.68	0.000*
Polishing time (min)	0.00005010	0.000574	0.87	0.402

S: 0.00574412, R^2: 88.7% and R^2 adjusted: 84.6%, *Significant at 95% CI

Table 8: Constant and coefficient for material removal rate (MRR)

Predictor	Coef.	SE	T	p
Constant	3.144	0.1734	18.13	0.000*
Grit size	-0.0007125	0.00006875	-10.36	0.000*
Axial load (N)	0.029531	0.004297	6.87	0.000*
Rotational speed (rpm)	0.00062679	0.0004911	12.76	0.000*
Polishing time (min)	0.041084	0.006875	5.98	0.000*

S: 0.0687485 R^2: 97.0% and R^2 adjusted: 95.9% CI

The regression coefficient Table 7 shows the linear fit coefficients for arithmetic average surface roughness R_a and the constant. It is observed that predictor's constant, grit size, axial load and rotational speed are more significant at 95% CI as it has p-value less than 0.005. The other predictor polishing time is not statistically significant as it has p-value more than 0.005. Correlation coefficient of 0.887 implies that the model has good fit with the experimental results.

It is observed from ANOVA table model comparison of arithmetic average surface roughness R_a shows that the model has well linear fit with the predicted values as the p-value is less than 0.05. It is seen from the ANOVA that the parameters grit size. Axial load and the polishing time have statistically significant effects on the response variable surface roughness. Further the model fir was checked using normal probability plot for the residuals of the response variable. Normal probability plot of the residuals for response R_a (Fig. 7) shows that the errors are normally distributed as the points in the plot will roughly form a straight line.

Regression analysis for MRR: The Eq. 2 describes the relationship between response Material Removal Rate (MRR) and predictor variables grit size, axial load (L), rotational speed (S) and polishing time (t).

The regression equation is:

$$MRR = 3.14-0.000713 \text{ grit size}+0.0295 L+0.000627 S +0.0411 t \quad (2)$$

The regression coefficient Table 8 shows the linear fit coefficients for Material Removal Rate (MRR) and the constant. It is observed that predictor's constant, grit size, axial load; rotational speed and polishing time are more significant at 95% CI as it has p-value less than 0.05. Correlation coefficient of 0.887 implies that the model has good fit with the experimental results.

Table 9: ANOVA for material removal rate (MRR)

Source	df	SS	MSA	F	p
Regression	4	1.6697	0.41743	88.32	0.000
Residual error	11	0.05199	0.00473		
Total	15	1.72169			

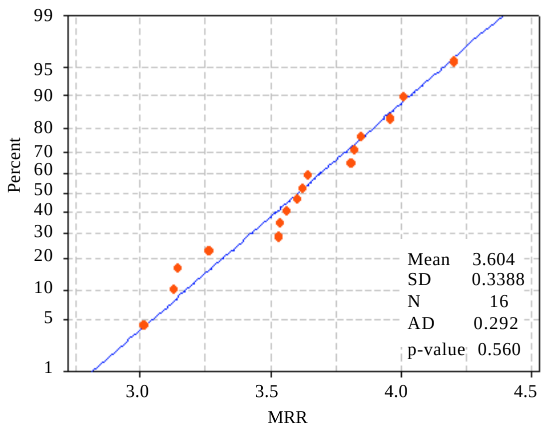


Fig. 8: Normal probability plot of the residual for response MRR

It is observed from ANOVA Table 9 that model comparison of MRR shows that the model has well linear fit with the predicted values as the p-value is less than 0.05. Normal probability plot of the residual for response Ra (Fig. 8) shows that the errors are normally distributed as the points in the plot will roughly form a straight line.

CONCLUSIONS

In this experiment, the surface of SS316L was polished by using Electrophoretic deposition assisted polishing (EPDAP) method. The surface quality can be distinctly improved in short period of time. The following conclusions can be drawn:

- In this experiment, the surface of SS316L was polished by using Electrophoretic deposition assisted polishing (EPDAP) method. The surface quality can be distinctly improved in short period of time. The following conclusions can be drawn. The surface roughness obtained up to 0.04557 μm (45.57 nm) in these experiments whose surface roughness before EPDAP method was 0.75 μm of stainless steel 316L. Hence, surface roughness reduction is achieved 93.92%
- The optimum polishing performance for the surface roughness is obtained at abrasive grit size 2000, Axial load (L) = 12 N, rotational speed (S) = 1500 rpm, polishing time (t) = 10 min. the surface roughness is decreases with decreasing in abrasive particle size
- EPDAP also improves in surface quality in terms of reflectivity
- The MRR = 4.2 mg min^{-1} is obtained maximum at abrasive grit size 1500, Axial load (L) = 20 N, Rotational speed (S) = 1500 rpm, Polishing time (t) = 15 min
- The grit size, factors axial load and rotational speed are more significant for electrophoretic deposition assisted polishing of SS316L

Thus the EPDAP is a very effective polishing process to improve surface finish.

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