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Research article

An investigative study on the parameters optimization of the electric discharge machining of Ti6Al4V

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Appendix 1

The experimental results of all the responses against all input factors as shown in Table A1.

Table A1. Experimental results of all the responses against all input factors.

Run order	HV	LV	T_{on}	T_{OFF}	Replic-ate no.	Duty Factor %	Machini-ng Time (sec)	MRR (g/min)	EW (g/min)	EW (mm^3/min)	Base Radius (R)	Surface Roughn-ess (R_a)
1	0.3	30	4	5.5	1	42%	2549	0.00111	0.00492	0.63	1.508	0.007
2	0.7	30	4	5.5	1	42%	2437	0.0018	0.00502	0.65	1.568	0.027
3	0.3	50	4	5.5	1	42%	2420	0.00149	0.00533	0.69	1.165	0.136
4	0.7	50	4	5.5	1	42%	1831	0.00164	0.00675	0.87	1.5	0.014
5	0.3	30	6.5	5.5	1	54%	2582	0.00186	0.00404	0.52	1.565	0.027
6	0.7	30	6.5	5.5	1	54%	2196	0.00232	0.00533	0.69	1.583	0.021
7	0.3	50	6.5	5.5	1	54%	2441	0.00143	0.00428	0.55	1.52	0.066
8	0.7	50	6.5	5.5	1	54%	1914	0.00241	0.00636	0.82	1.592	0.039
9	0.3	30	4	6.5	1	38%	2823	0.00176	0.00349	0.45	1.597	0.022

Continued on next page

Run order	HV	LV	T_{on}	T_{OFF}	Replic-ate no.	Duty Factor %	Machini-ng Time (sec)	MRR (g/min)	EW (g/min)	EW (mm^3/min)	Base Radius (R)	Surface Roughn-ess (R_a)
10	0.7	30	4	6.5	1	38%	2995	0.001	0.00421	0.54	1.168	0.021
11	0.3	50	4	6.5	1	38%	2008	0.00209	0.00604	0.78	1.218	0.014
12	0.7	50	4	6.5	1	38%	2854	0.00126	0.00435	0.56	1.327	0.013
13	0.3	30	6.5	6.5	1	50%	2090	0.00138	0.0058	0.75	1.394	0.042
14	0.7	30	6.5	6.5	1	50%	1951	0.00191	0.00584	0.75	1.493	0.009
15	0.3	50	6.5	6.5	1	50%	2374	0.00195	0.00473	0.61	1.586	0.023
16	0.7	50	6.5	6.5	1	50%	2161	0.00236	0.00491	0.63	1.515	0.014
17	0.3	30	4	5.5	2	42%	3030	0.00111	0.00398	0.51	1.069	0.019
18	0.7	30	4	5.5	2	42%	2917	0.00132	0.00405	0.52	0.98	0.082
19	0.3	50	4	5.5	2	42%	2424	0.00126	0.0052	0.67	1.157	0.038
20	0.7	50	4	5.5	2	42%	2549	0.00146	0.00464	0.6	1.01	0.076
21	0.3	30	6.5	5.5	2	54%	2784	0.00185	0.00388	0.5	1.551	0.044
22	0.7	30	6.5	5.5	2	54%	2686	0.00156	0.00395	0.51	1.594	0.034
23	0.3	50	6.5	5.5	2	54%	2287	0.00213	0.0058	0.75	1.58	0.042
24	0.7	50	6.5	5.5	2	54%	1375	0.00266	0.00938	1.21	1.269	0.055
25	0.3	30	4	6.5	2	38%	2162	0.00108	0.00597	0.77	1.131	0.031
26	0.7	30	4	6.5	2	38%	3327	0.00117	0.00373	0.48	1.491	0.01
27	0.3	50	4	6.5	2	38%	2766	0.00148	0.00438	0.56	1.239	0.045
28	0.7	50	4	6.5	2	38%	2715	0.00139	0.0048	0.62	1.581	0.01
29	0.3	30	6.5	6.5	2	50%	2123	0.00223	0.00591	0.76	1.632	0.018
30	0.7	30	6.5	6.5	2	50%	2469	0.00104	0.00462	0.59	1.559	0.041
31	0.3	50	6.5	6.5	2	50%	1896	0.00291	0.00598	0.77	1.557	0.054
32	0.7	50	6.5	6.5	2	50%	2225	0.00186	0.00464	0.6	1.52	0.013
33	0.3	30	4	5.5	3	42%	3451	0.00108	0.0033	0.43	1.565	0.019
34	0.7	30	4	5.5	3	42%	3323	0.00135	0.00361	0.47	1.565	0.054
35	0.3	50	4	5.5	3	42%	1964	0.00171	0.00574	0.74	1.528	0.054
36	0.7	50	4	5.5	3	42%	2775	0.00166	0.00467	0.6	1.619	0.02
37	0.3	30	6.5	5.5	3	54%	3102	0.00174	0.00368	0.47	1.664	0.014
38	0.7	30	6.5	5.5	3	54%	3136	0.00145	0.00304	0.39	1.596	0.019
39	0.3	50	6.5	5.5	3	54%	2648	0.00213	0.00403	0.52	1.542	0.06
40	0.7	50	6.5	5.5	3	54%	2406	0.00182	0.00434	0.56	1.636	0.015
41	0.3	30	4	6.5	3	38%	3048	0.00136	0.00431	0.56	1.324	0.106
42	0.7	30	4	6.5	3	38%	2785	0.00155	0.00317	0.41	1.571	0.013
43	0.3	50	4	6.5	3	38%	2721	0.0015	0.00454	0.59	1.534	0.01
44	0.7	50	4	6.5	3	38%	2153	0.00284	0.00608	0.78	1.518	0.034
45	0.3	30	6.5	6.5	3	50%	2680	0.00128	0.00423	0.54	1.575	0.032
46	0.7	30	6.5	6.5	3	50%	2845	0.00167	0.0039	0.5	1.631	0.009
47	0.3	50	6.5	6.5	3	50%	1383	0.00265	0.00881	1.13	1.481	0.02
48	0.7	50	6.5	6.5	3	50%	1677	0.00225	0.00741	0.95	1.557	0.019

Appendix 2. Surface roughness and base radius for Ti6Al4V

Figures A1–A3 show the side view of the Ti6Al4Vworkpieces when the hardness and base radius were being calculated.

The values are tabulated and are presented as Table A2.

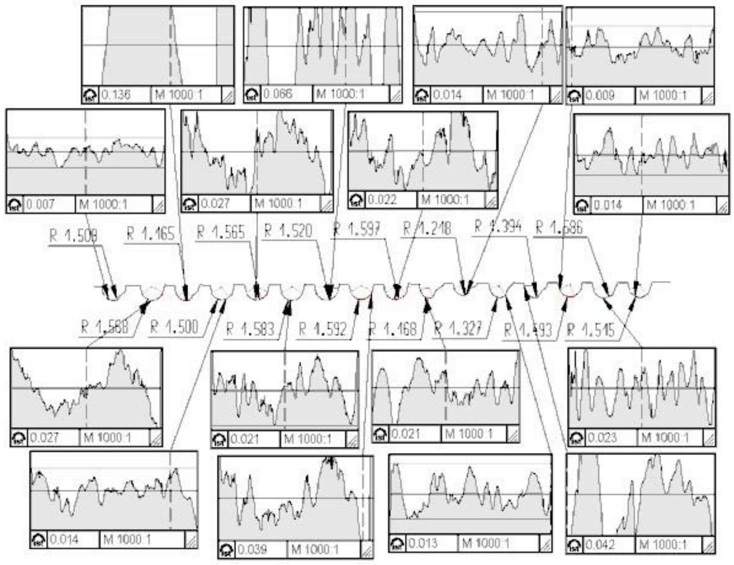

Figure A1. Roughness and base radius values of Ti6Al4V piece 1—side 1.

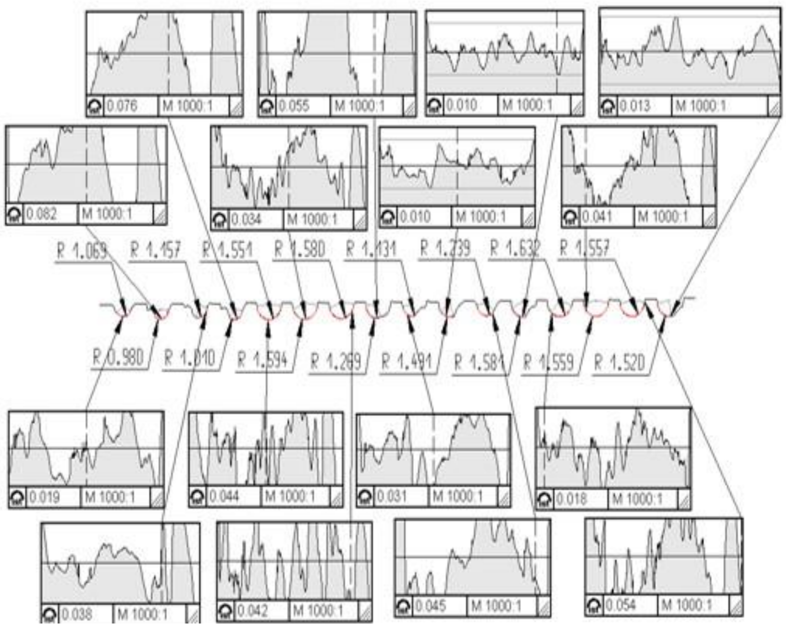

Figure A2. Roughness and base radius values of Ti6Al4V piece 1—Side 2.

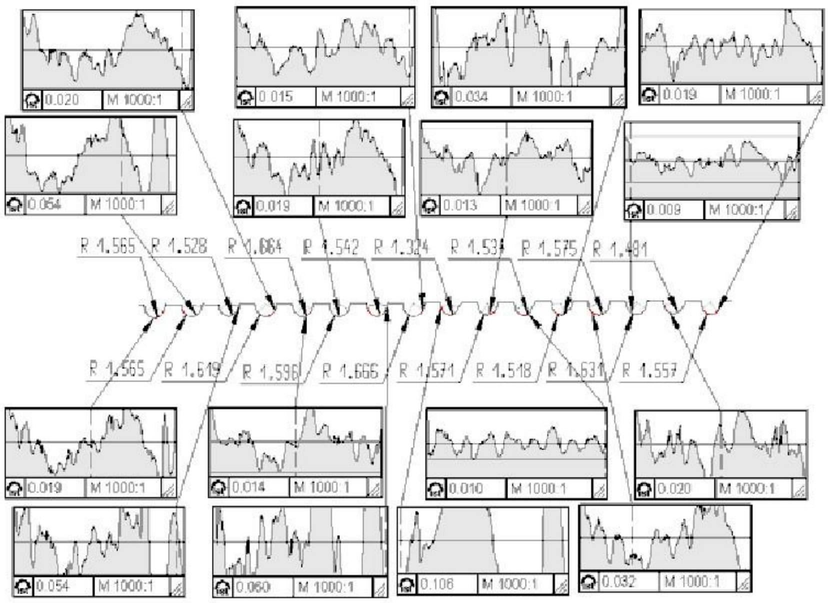

Figure A3. Roughness and base radius values of Ti6Al4V piece 2—side 1.

Table A2. Surface roughness values of Ti6Al4V.

Surface Roughness Values for Ti6Al4V				
Replicate No.	1	2	3	Mean
1	0.007	0.019	0.019	0.015
2	0.027	0.082	0.054	0.054
3	0.136	0.038	0.054	0.076
4	0.014	0.076	0.02	0.037
5	0.027	0.044	0.014	0.028
6	0.021	0.034	0.019	0.025
7	0.066	0.042	0.06	0.056
8	0.039	0.055	0.015	0.036
9	0.022	0.031	0.106	0.053
10	0.021	0.01	0.013	0.015
11	0.014	0.045	0.01	0.023
12	0.013	0.01	0.034	0.019
13	0.042	0.018	0.032	0.031
14	0.009	0.041	0.009	0.02
15	0.023	0.054	0.02	0.032
16	0.014	0.013	0.019	0.015

Appendix 3. Analysis of results of Ti6Al4V

The Minitab Analysis of the results of responses on Ti6AL4V will be discussed in this section.

Appendix 3.1. Analysis of results of machining time (Tm) for Ti6Al4V

The ANOVA table in Table A3 as well as the Normal Probability Plot in Figure A4 and residual plot in Figure A5 indicates that LV and T_{on} are significant factors when considering Tm for Ti6Al4V. Now, the model is refitted by eliminating the non significant values and considering only LV and T_{on} as input factors.

Table A3. ANOVA table of Tm for Ti6Al4V considering all factors.

Factorial Fit: Tm versus HV, LV, T_{ON}, T_{OFF}

Estimated Effects and Coefficients for Tm (coded units)

Term	Effect	Coef	SE Coef	T	P
Constant		2488.7	57.67	43.16	0.000
HV	−2.3	−1.1	57.67	−0.02	0.985
LV	−480.2	−240.1	57.67	−4.16	0.000
T_{ON}	−358.2	−179.1	57.67	−3.11	0.004
T_{OFF}	−124.8	−62.4	57.67	−1.08	0.287
HV*LV	−55.8	−27.9	57.67	−0.48	0.632
HV*T_{ON}	−110.2	−55.1	57.67	−0.96	0.347
HV*T_{OFF}	175.8	87.9	57.67	1.52	0.137
LV*T_{ON}	−7.9	−4.0	57.67	−0.07	0.946
LV*T_{OFF}	116.4	58.2	57.67	1.01	0.320
T_{ON}*T_{OFF}	−182.1	−91.0	57.67	−1.58	0.124
HV*LV*T_{ON}	−43.6	−21.8	57.67	−0.38	0.708
HV*LV*T_{OFF}	−11.6	−5.8	57.67	−0.10	0.921
HV*T_{ON}*T_{OFF}	66.9	33.5	57.67	0.58	0.566
LV*T_{ON}*T_{OFF}	−35.3	−17.7	57.67	−0.31	0.761
HV*LV*T_{ON}*T_{OFF}	117.3	58.7	57.67	1.02	0.317

S = 399.526 PRESS = 11492703
R−Sq = 53.46% R−Sq(pred) = 0.00% R−Sq(adj) = 31.64%

Analysis of Variance for Tm (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	4493182	4493182	1123295	7.04	0.000
2-Way Interactions	6	1115295	1115295	185883	1.16	0.349
3-Way Interactions	4	93120	93120	23280	0.15	0.964
4-Way Interactions	1	165205	165205	165205	1.03	0.317
Residual Error	32	5107868	5107868	159621		
Pure Error	32	5107868	5107868	159621		
Total	47	10974670				

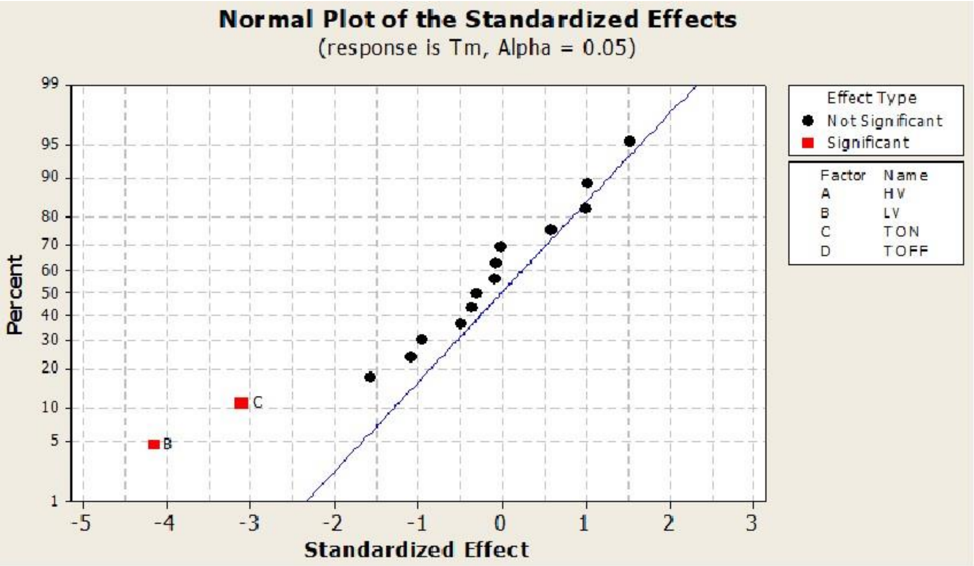

Figure A4. Normal probability plot of the standardized effects of Tm for Ti6Al4V considering all factors.

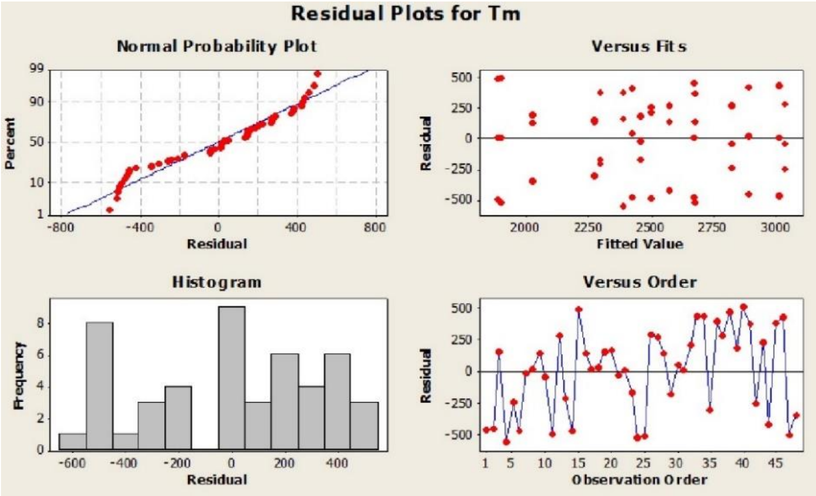

Figure A5. Residual plot of Tm for Ti6Al4V considering all factors.

The p-values from the ANOVA table in Table A4 of the refitted MODEL indicate that the models as well as these factors are significant.

Table A4. ANOVA table of Tm for Ti6Al4V considering significant factor.

Factorial Fit: Tm versus HV, LV, T_{ON}, T_{OFF}

Estimated Effects and Coefficients for Tm (coded units)

Term Effect	Coef	SE	Coef	T	P
Constant		2488.7	57.67	43.16	0
HV	−2.3	−1.1	57.67	−0.02	0.985
LV	−480.2	−240.1	57.67	−4.16	0
T_{ON}	−358.2	−179.1	57.67	−3.11	0.004
T_{OFF}	−124.8	−62.4	57.67	−1.08	0.287
HV*LV	−55.8	−27.9	57.67	−0.48	0.632
HV*T_{ON}	−110.2	−55.1	57.67	−0.96	0.347
HV*T_{OFF}	175.8	87.9	57.67	1.52	0.137
LV*T_{ON}	−7.9	−4	57.67	−0.07	0.946
LV*T_{OFF}	116.4	58.2	57.67	1.01	0.32
T_{ON}*T_{OFF}	−182.1	−91	57.67	−1.58	0.124
HV*LV*T_{ON}	−43.6	−21.8	57.67	−0.38	0.708
HV*LV*T_{OFF}	−11.6	−5.8	57.67	−0.1	0.921
HV*T_{ON}*T_{OFF}	66.9	33.5	57.67	0.58	0.566
LV*T_{ON}*T_{OFF}	−35.3	−17.7	57.67	−0.31	0.761
HV*LV*T_{ON}*T_{OFF}	117.3	58.7	57.67	1.02	0.317

S = 399.526   PRESS = 11492703

R−Sq = 53.46%   R−Sq(pred) = 0.00%   R−Sq(adj) = 31.64%

Analysis of Variance for Tm (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	4	4493182	4493182	1123295	7.04	0
2-Way	6	1115295	1115295	185883	1.16	0.349
3-Way	4	93120	93120	23280	0.15	0.964
4-Way	1	165205	165205	165205	1.03	0.317
Residual	32	5107868	5107868	159621		
Pure	32	5107868	5107868	159621		
Total	47	10974670				

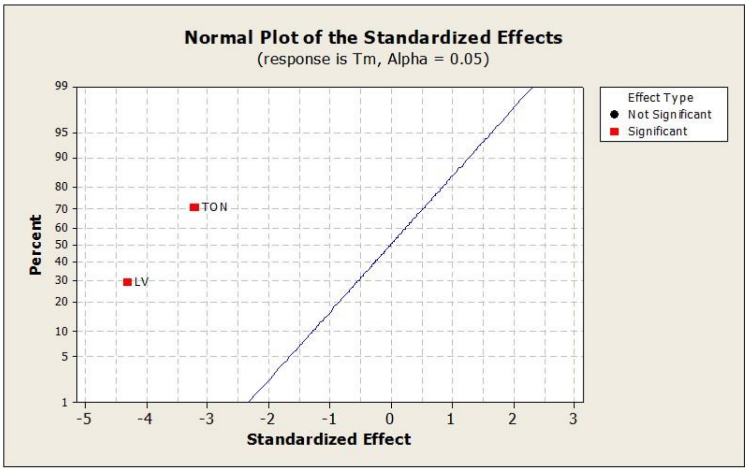

Figure A6. Normal probability plot of the standardized effects of Tm for Ti6Al4V considering significant factors.

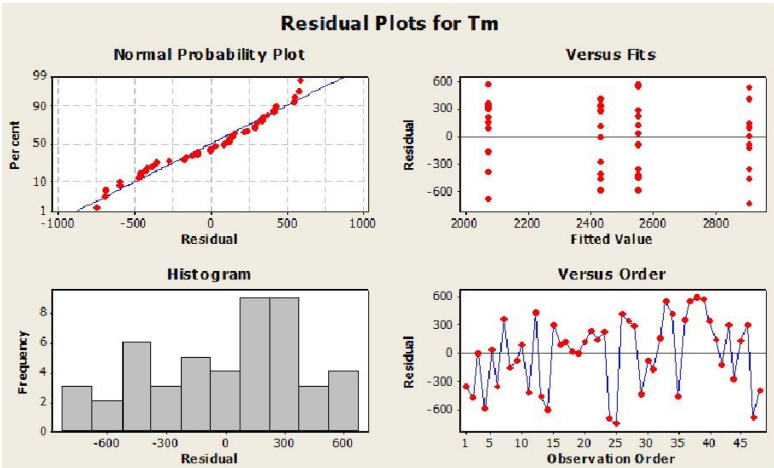

Figure A7. Residual plot of Tm for Ti6Al4V considering all factors.

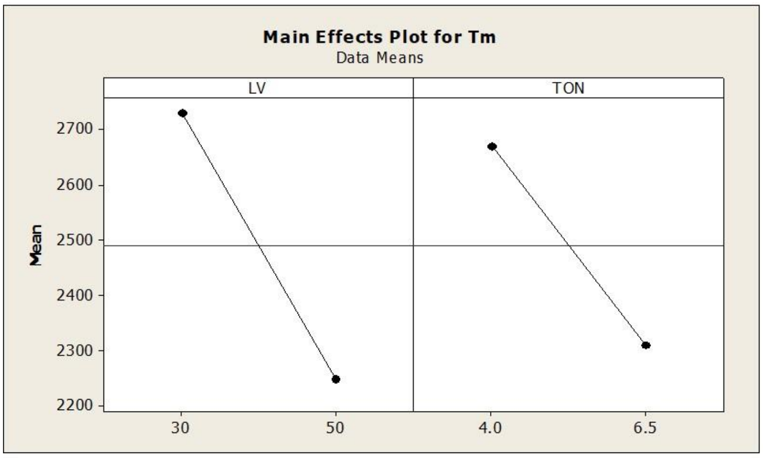

Figure A8. Main effects plot of Tm for Ti6Al4V considering significant factors.

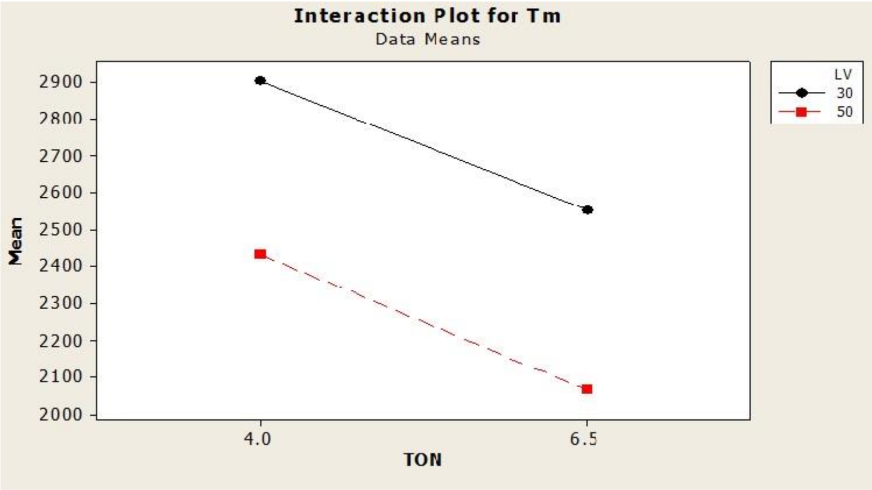

Figure A9. Residual plot of Tm for Ti6Al4V considering T_{ON} & LV.

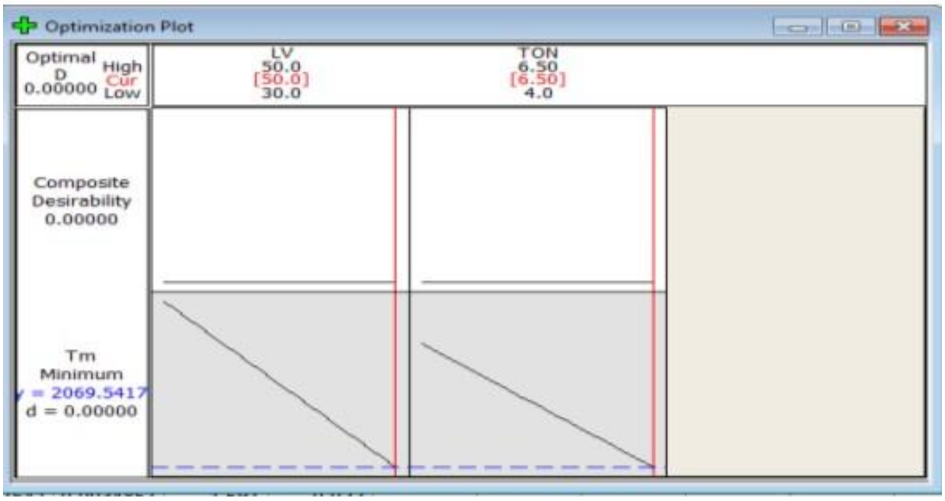

Figure A10. Optimization plot of Tm for Ti6Al4V for significant factors.

After developing the ANOVA tables for significant factors the Main Effects Plot in Figure A8 as well as the Interaction Plot mentioned in Figure A9 is prepared. The main effects plot shows steep slope of means indicating the significance of these factors.

The interaction plot in Figure A10 shows non parallel lines of significance.

Next, the optimized values of significant factors are to be calculated. For optimization of Machining Time we have set the Target Value to '0' while the Upper Value to '1375 sec' which is the minimum value of machining time and then the value of Desirability functions is evaluated.

d = 0 emphasizes that y or response is more away from the target that is "Less emphasis on the Target", because the target was taken as "0" and response comes out to be far away from it (rather far from the Upper value that was taken as 1375). It could have been d = 1 or close to 1, if the target was set close to 1500 and upper value was taken as greater than say 2200.

The Optimized value for LV is 50 A while for T_{ON} is 6.5 µs. For these values minimum Tm is 2069.5417 seconds

Appendix 3.2. Analysis of results of material removal rate (MRR) for Ti6Al4V

Table A5. ANOVA table of MRR for Ti6Al4V considering all factors.

Factorial Fit: MRR versus HV, LV, T_{ON}, T_{OFF}

Estimated Effects and Coefficients for MRR (coded units)

Term Effect	Coef	SE	Coef	T	P
Constant		0.001715	0.000058	29.51	0
HV	0.000051	0.000026	0.000058	0.44	0.662
LV	0.000431	0.000216	0.000058	3.71	0.001
T_{ON}	0.000474	0.000237	0.000058	4.08	0
T_{OFF}	0.000068	0.000034	0.000058	0.58	0.565
HV*LV	0.000025	0.000013	0.000058	0.22	0.83
HV*T_{ON}	−0.000068	−0.000034	0.000058	−0.58	0.565
HV*T_{OFF}	−0.000164	−0.000082	0.000058	−1.41	0.169
LV*T_{ON}	0.00009	0.000045	0.000058	0.78	0.444
LV*T_{OFF}	0.000161	0.00008	0.000058	1.38	0.176
T_{ON}*T_{OFF}	−0.000058	−0.000029	0.000058	−0.5	0.621
HV*LV*T_{ON}	0.000022	0.000011	0.000058	0.19	0.85
HV*LV*T_{OFF}	−0.000013	−0.000006	0.000058	−0.11	0.913
HV*T_{ON}*T_{OFF}	−0.000036	−0.000018	0.000058	−0.31	0.756
LV*T_{ON}*T_{OFF}	0.000063	0.000032	0.000058	0.55	0.589
HV*LV*T_{ON}*T_{OFF}	−0.000161	−0.000081	0.000058	−1.39	0.175

S = 0.000402656 PRESS = 0.0000116735

R−Sq = 54.57% R−Sq(pred) = 0.00% R−Sq(adj) = 33.27%

Analysis of Variance for MRR (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	4	0.00000502	0.00000502	0.00000125	7.73	0
2-Way	6	0.00000083	0.00000083	0.00000014	0.86	0.538
3-Way	4	0.00000007	0.00000007	0.00000002	0.11	0.978
4-Way	1	0.00000031	0.00000031	0.00000031	1.93	0.175
Residual	32	0.00000519	0.00000519	0.00000016		
Pure	32	0.00000519	0.00000519	0.00000016		
Total	47	0.00001142				

Unusual Observations for MRR

Obs	StdOrder	MRR	Fit	SE Fit	Residual	St Resid
44	44	0.002843	0.001832	0.000232	0.001010	3.07R

R denotes an observation with a large standardized residual.

Estimated Coefficients for MRR using data in uncoded units

Term	Coef
Constant	−0.0445804
HV	0.0815985
LV	0.00107131
T_{ON}	0.00900231
T_{OFF}	0.00740601
HV*LV	−0.00201105
HV* T_{ON}	−0.0149229
HV*T_{OFF}	−0.013347
LV* T_{ON}	−2.23E-04
LV*T_{OFF}	−1.77E-04
T_{ON} *T_{OFF}	−0.00146677
HV*LV* T_{ON}	0.000391549
HV*LV*T_{OFF}	0.00033235
HV* T_{ON} *T_{OFF}	0.00243508
LV* T_{ON} *T_{OFF}	3.73E-05
HV*LV* T_{ON} *T_{OFF}	−6.45E-05

The ANOVA table in Table A5 for MRR is prepared in Minitab considering all factors and then the significant factors are determined having p-value less than 0.05. The goal is kept in mind i.e. Maximization of Material Removal Rate.

The ANOVA table as well as the Normal Probability Plot in Figure A11 indicates that LV and T_{ON} are significant factors when considering MRR for Ti6Al4V. Now, the model is refitted by eliminating the non significant values and considering only LV and T_{ON} as input factors.

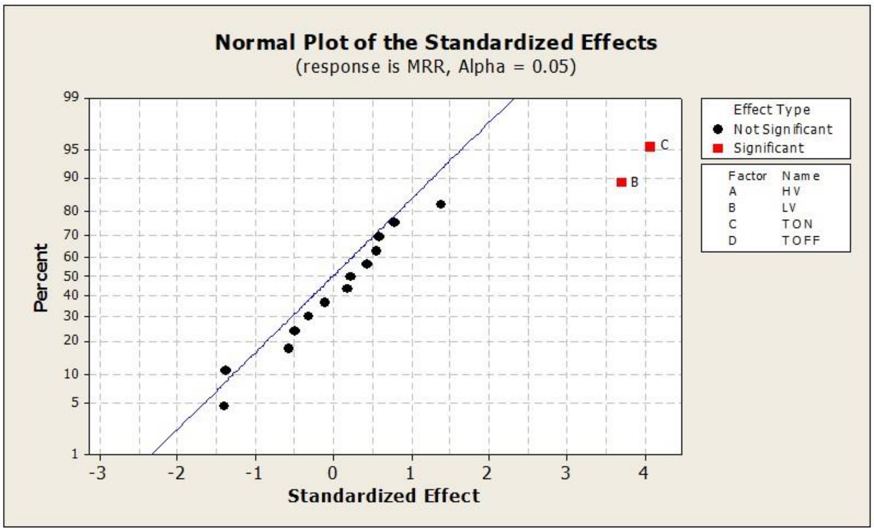

Figure A11. Normal probability plot of the standardized effects of MRR for Ti6Al4V considering all factors.

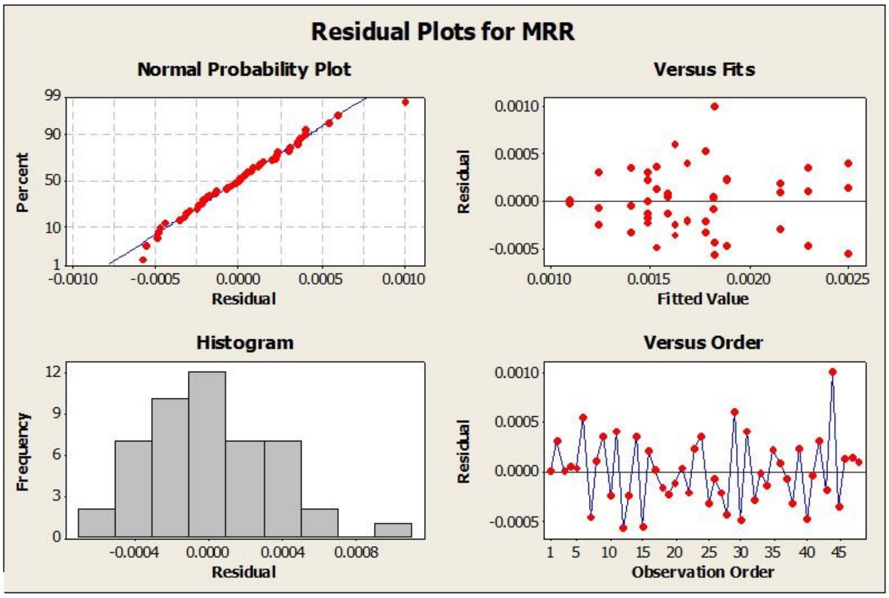

Figure A12. Residual plot of MRR for Ti6Al4V considering all factors.

The p-values from the ANOVA table in Table A6 of the refitted MODEL indicate that the models as well as these factors are significant.

Table A6. ANOVA table of MRR for Ti6Al4V considering significant factors.

Factorial Fit: MRR versus LV, T_{ON}						
Estimated Effects and Coefficients for MRR (coded units)						
Term Effect		Coef	SE	Coef	T	P
Constant			0.001715	0.000055	31.29	0
LV		0.000431	0.000216	0.000055	3.93	0
T_{ON}		0.000474	0.000237	0.000055	4.32	0
S = 0.000379792		PRESS = 7.385201E-06				
R−Sq = 43.16%		R−Sq(pred) = 35.33%		R−Sq(adj) = 40.64%		
Analysis of Variance for MRR (coded units)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	2	0.00000493	0.00000493	0.00000246	17.09	0
Residual	45	0.00000649	0.00000649	0.00000014		
Lack of fit	1	0.0000001	0.0000001	0.0000001	0.67	0.417
Pure	44	0.00000639	0.00000639	0.00000015		
Total	47	0.00001142				
Unusual Observations for MRR						
Obs	StdOrder	MRR	Fit	SE Fit	Residual	StResid
7	7	0.001426	0.002168	0.000095	−0.000742	−2.02R
31	31	0.002911	0.002168	0.000095	0.000744	2.02R
44	44	0.002843	0.001694	0.000095	0.001149	3.12R
R denotes an observation with a large standardized residual.						
Estimated Coefficients for MRR using data in uncoded units						
Term		Coef				
Constant		−1.42938E-04				
LV		2.15673E-05				
T_{ON}		0.000189610				

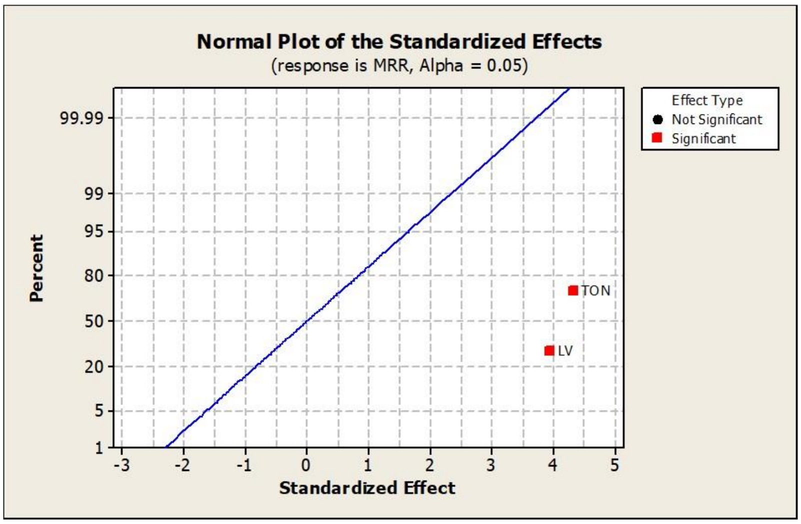

Figure A13. Normal probability plot of the standardized effects of MRR for Ti6Al4V considering significant factors.

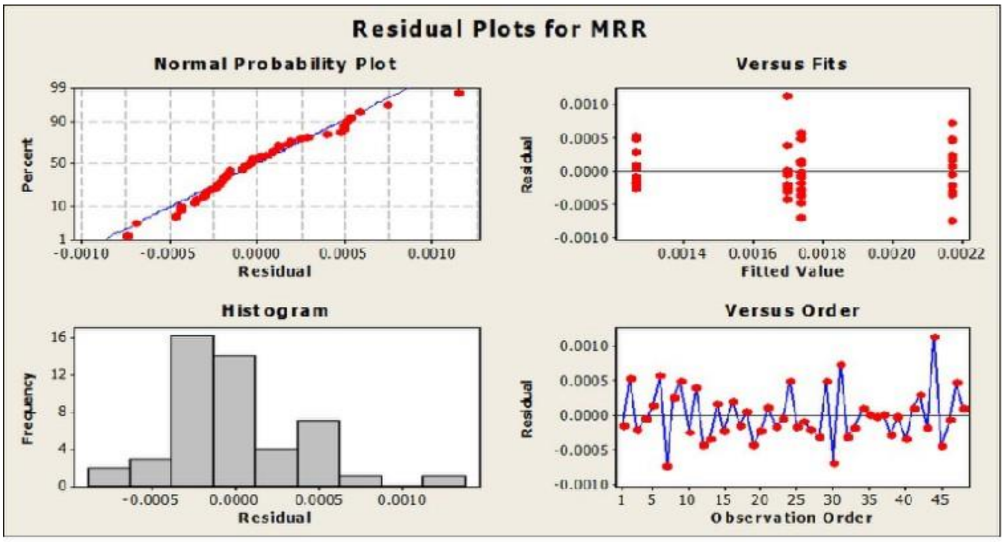

Figure A14. Residual plot of MRR for Ti6Al4V considering all factors.

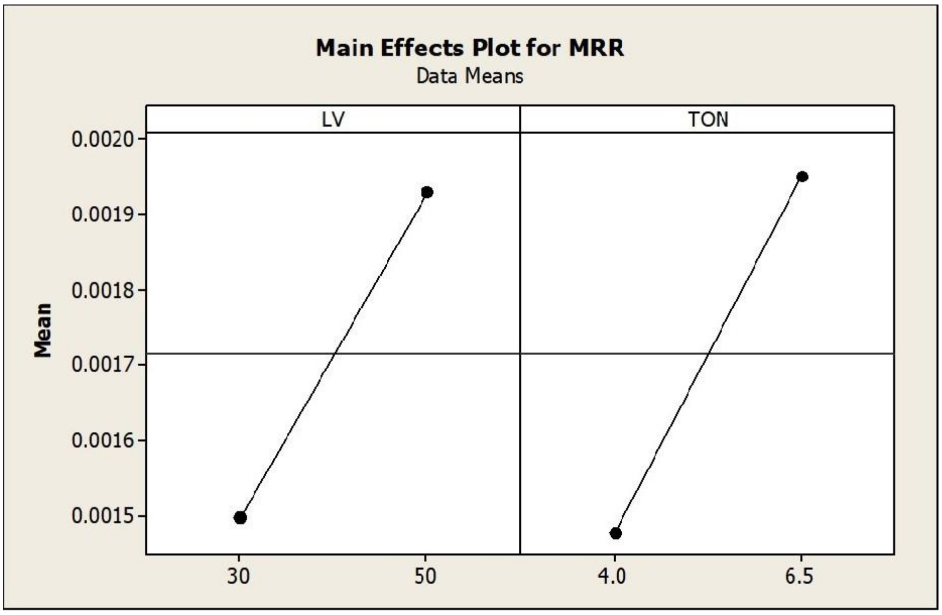

Figure A15. Main effects plot of MRR for Ti6Al4V considering significant factors.

After developing the ANOVA tables for significant factors the Main Effects Plot in Figure A15 as well as the Interaction Plot in Figure A16 is prepared for MRR. The main effects plot shows steep slope of means indicating the significance of these factors. The interaction plot in Figure A16 shows non parallel lines of significance.

Next, the optimized values of significant factors are to be calculated. For optimization of Material Removal Rate we have set the Target Value to '1' while the Lower Value to '0.00291 g/min' which is the Maximum value of Material Removal Rate and then the value of Desirability functions is evaluated. d = 0 emphasizes that y or response is more away from the target that is "Less emphasis on the Target", because the target was taken as "1" and response comes out to be far away from it (rather far from the lower value that was taken as .00291). It could have been d = 1 or close to 1, if the target was set close to .002 and lower value was taken as less than say 0.001.

The Optimized value for LV is 50 A while for T_{ON} is 6.5 µs. For these values maximum MRR is 0.0022 g/min (Figure A17).

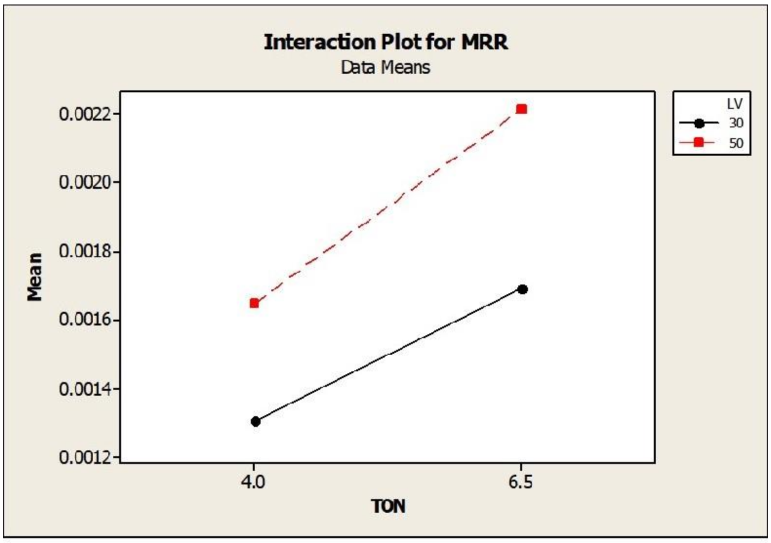

Figure A16. Residual plot of MRR for Ti6Al4V considering T_{ON} & LV.

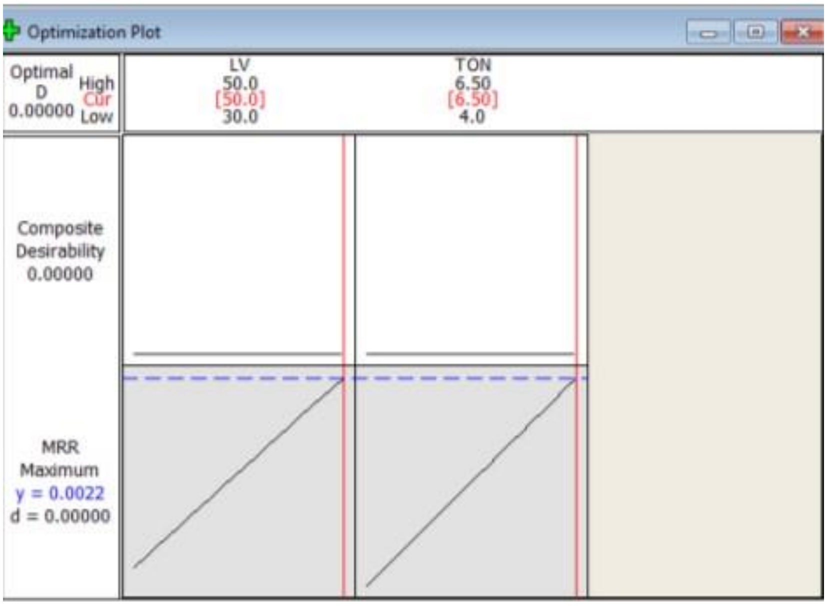

Figure A17. Optimization plot of MRR for Ti6Al4V for significant factors.

Appendix 3.3. Analysis of results of electrode wear rate (EWR) for Ti6Al4V

The ANOVA table in Table A7 for EWR is prepared in Minitab considering all factors and then the significant factors are determined having p-value less than 0.05. The goal is kept in mind i.e. Minimization of Electrode Wear Rate.

Table A7. ANOVA table of EW for Ti6Al4V considering all factors.

Factorial Fit: EW versus HV, LV, T_{ON}, T_{OFF}

Estimated Effects and Coefficients for EW (coded units)

Term Effect	Coef	SE	Coef	T	P
Constant		0.004941	0.000175	28.25	0
HV	0.000018	0.000009	0.000175	0.05	0.959
LV	0.001217	0.000609	0.000175	3.48	0.001
T_{ON}	0.000525	0.000263	0.000175	1.5	0.143
T_{OFF}	0.000272	0.000136	0.000175	0.78	0.442
HV*LV	0.000271	0.000136	0.000175	0.78	0.444
HV*T_{ON}	0.000195	0.000097	0.000175	0.56	0.582
HV*T_{OFF}	−0.000562	−0.000281	0.000175	−1.61	0.118
LV*T_{ON}	0.000154	0.000077	0.000175	0.44	0.663
LV*T_{OFF}	−0.00026	−0.00013	0.000175	−0.74	0.463
T_{ON}*T_{OFF}	0.00045	0.000225	0.000175	1.29	0.207
HV*LV*T_{ON}	0.000085	0.000042	0.000175	0.24	0.81
HV*LV*T_{OFF}	−0.000109	−0.000054	0.000175	−0.31	0.758
HV*T_{ON}*T_{OFF}	−0.00034	−0.00017	0.000175	−0.97	0.338
LV*T_{ON}*T_{OFF}	−0.000081	−0.000041	0.000175	−0.23	0.818
HV*LV*T_{ON}*T_{OFF}	−0.00041	−0.000205	0.000175	−1.17	0.249
S = 0.00121184	R−Sq = 42.23%	R−Sq(adj) = 15.15%			

Analysis of Variance for EW (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	4	0.00002198	0.00002198	0.0000055	3.74	0.013
2-Way	6	0.00000866	0.00000866	0.00000144	0.98	0.453
3-Way	4	0.0000017	0.0000017	0.00000042	0.29	0.883
4-Way	1	0.00000202	0.00000202	0.00000202	1.38	0.249
Residual	32	0.00004699	0.00004699	0.00000147		
Pure	32	0.00004699	0.00004699	0.00000147		
Total	47	0.00008135				

Unusual Observations for EW

Obs	StdOrder	EW	Fit	SE Fit	Residual	StResid
24	24	0.00938	0.006693	0.0007	0.002687	2.72R
40	40	0.00434	0.006693	0.0007	−0.002353	−2.38R
47	47	0.00881	0.006507	0.0007	0.002303	2.33R

R denotes an observation with a large standardized residual

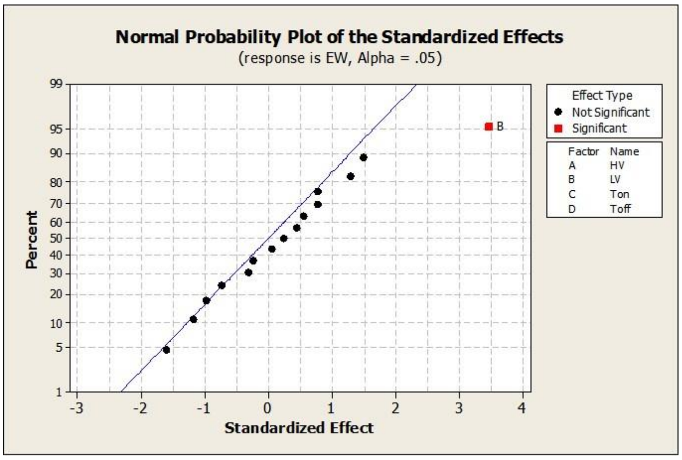

Figure A18. Normal probability plot of the standardized effects of EW for Ti6Al4V considering all factors.

The ANOVA table in Table A7 as well as the Normal Probability Plot in Figure A18 ndicates that LV is a significant factor when considering EW for Ti6Al4V. Now, the model is refitted by eliminating the non significant values and considering only LV as an input factor.

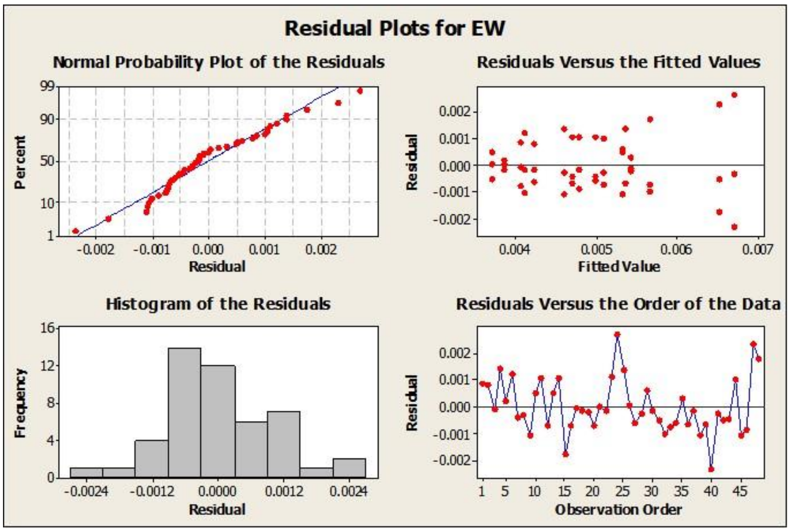

Figure A19. Residual plot of EW for Ti6Al4V considering all factors.

The p-values from the ANOVA table in Table A8 of the refitted MODEL indicate that the models as well as these factors are significant.

Table A8. ANOVA table of EW for Ti6Al4V considering significant factors.

Factorial Fit: EW versus LV

Estimated Effects and Coefficients for EW (coded units)

Term Effect	Coef	SE	Coef	T	P
Constant		0.004941	0.000170	29.12	0.000
LV	0.001217	0.000609	0.000170	3.59	0.001

S = 0.00117559 R-Sq = 21.85% R-Sq(adj) = 20.15%

Analysis of Variance for EW (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	1	0.00001778	0.00001778	0.00001778	12.86	0.001
Residual	46	0.00006357	0.00006357	0.00000138		
Pure	46	0.00006357	0.00006357	0.00000138		
Total	47	0.00008135				

Unusual Observations for EW

Obs	StdOrder	EW	Fit	SE Fit	Residual	St Resid
24	24	0.009380	0.005550	0.000240	0.003830	3.33R
47	47	0.008810	0.005550	0.000240	0.003260	2.83R

R denotes an observation with a large standardized residual.

Estimated Coefficients for EW using data in uncoded units

Term	Coef
Constant	0.00250688
LV	6.08542E-05

Note Normal and Pareto effects plots require at least 3 terms.

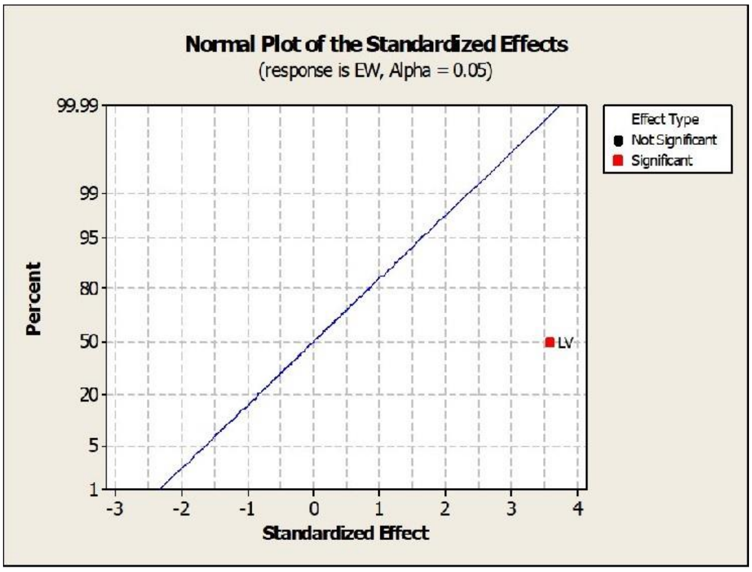

Figure A20. Normal probability plot of the standardized effects of EW for Ti6Al4V considering significant factors.

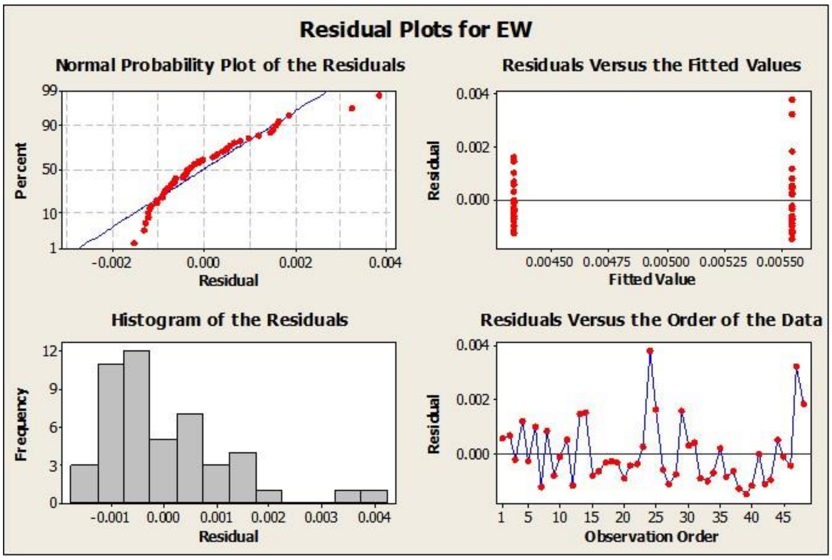

Figure A21. Residual plot of EW for Ti6Al4V considering all factors.

After developing the ANOVA tables for significant factors the Main Effects Plot in Figure A22 as well as the Interaction Plot in Figure A23 is prepared for EWR. The main effects plot shows steep slope of means indicating the significance of this factors.The interaction plot in Figure A24 shows non parallel lines of significance.

Next, the optimized values of significant factors are to be calculated. For optimization of Material Removal Rate we have set the Target Value to '0' while the Upper Value to '0.00304' which is the Minimum value of Electrode Wear Rate and then the value of Desirability functions is evaluated.

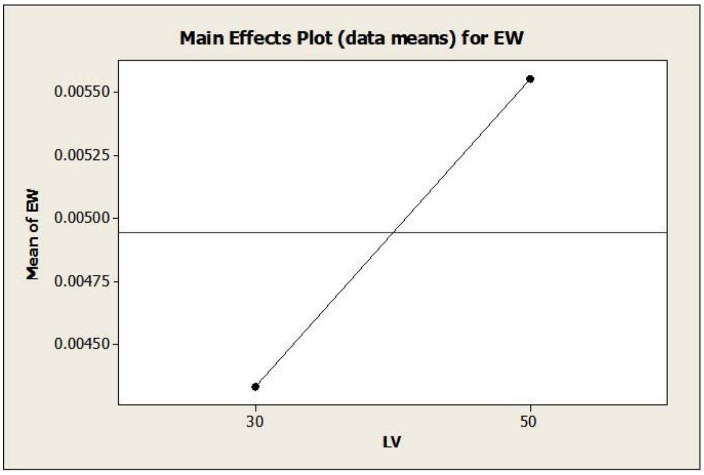

Figure A22. Main effects plot of EW for Ti6Al4V considering significant factors.

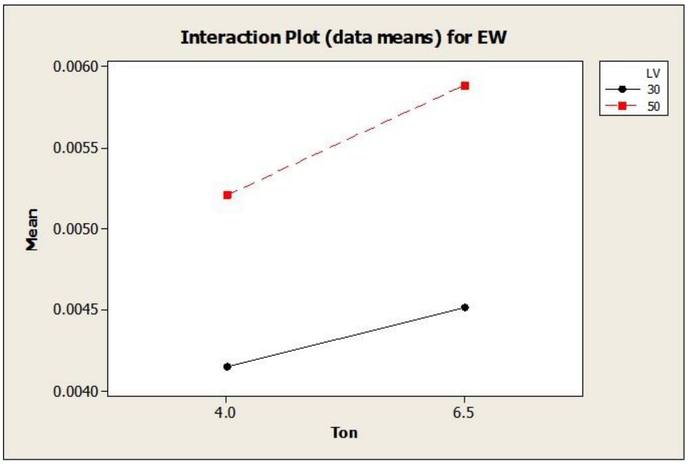

Figure A23. Residual plot of EW for Ti6Al4V considering T_{ON} & LV.

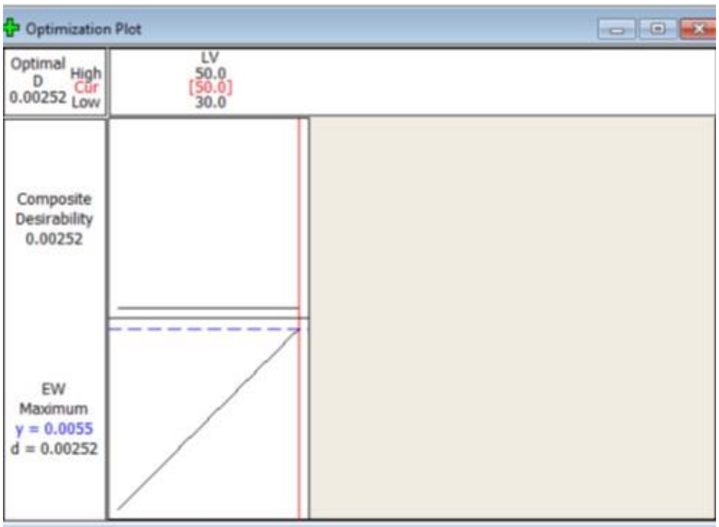

Figure A24. Optimization plot of EW for Ti6Al4V for significant factors.

d = 0.00252 emphasizes that y or response is more away from the target that is "Less emphasis on the Target", because the target was taken as "1" and response comes out to be far away from it (rather far from the Upper value that was taken as .00304). It could have been d = 1 or close to 1, if the target was set close to 0.004 and upper value was taken as greater than say 0.006.

The Optimized value for LV is 30 A for which values minimum EWR is 0.0055 g/min.

Appendix 3.4. Analysis of results of surface roughness (Ra) for Ti6Al4V

The ANOVA table in Table A9 for Ra is prepared in Minitab considering all factors and then the significant factors are determined having p-value less than 0.05. The goal is kept in mind i.e. Minimization of Surface Roughness.

The ANOVA table as well as the Normal Probability Plot in Figure A25 indicates that T_{OFF} and interaction of ***HV*LV*T_{OFF}*** are significant factors when considering Ra for Ti6Al4V. Now, the model is refitted by eliminating the non significant values and considering only T_{OFF} and HV*LV*T_{OFF} as input factors.

Table A9. ANOVA table of Ra for Ti6Al4V considering all factors.

Factorial Fit: Ra versus HV, LV, T_{ON}, T_{OFF}

Estimated Effects and Coefficients for Ra (coded units)

Term Effect	Coef	SE	Coef	T	P
Constant		0.033438	0.00345	9.69	0
HV	−0.011708	−0.005854	0.00345	−1.7	0.099
LV	0.006792	0.003396	0.00345	0.98	0.332
T_{ON}	−0.006042	−0.003021	0.00345	−0.88	0.388
T_{OFF}	−0.014958	−0.007479	0.00345	−2.17	0.038
HV*LV	−0.008292	−0.004146	0.00345	−1.2	0.238
HV*T_{ON}	−0.001125	−0.000563	0.00345	−0.16	0.872
HV*T_{OFF}	−0.005875	−0.002937	0.00345	−0.85	0.401
LV*T_{ON}	0.002375	0.001187	0.00345	0.34	0.733
LV*T_{OFF}	−0.013875	−0.006938	0.00345	−2.01	0.053
T_{ON}*T_{OFF}	0.003125	0.001562	0.00345	0.45	0.654
HV*LV*T_{ON}	0.002792	0.001396	0.00345	0.4	0.688
HV*LV*T_{OFF}	0.015375	0.007687	0.00345	2.23	0.033
HV*T_{ON}*T_{OFF}	0.004708	0.002354	0.00345	0.68	0.5
LV*T_{ON}*T_{OFF}	0.003375	0.001688	0.00345	0.49	0.628
HV*LV*T_{ON}*T_{OFF}	−0.012875	−0.006437	0.00345	−1.87	0.071

S = 0.0239013 R−Sq = 44.05% R−Sq(adj) = 17.82%

Analysis of Variance for Ra (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	4	0.0053216	0.0053216	0.0013304	2.33	0.077
2-Way	6	0.0037495	0.0037495	0.0006249	1.09	0.387
3-Way	4	0.0033329	0.0033329	0.0008332	1.46	0.238
4-Way	1	0.0019892	0.0019892	0.0019892	3.48	0.071
Residual	32	0.0182807	0.0182807	0.0005713		
Pure	32	0.0182807	0.0182807	0.0005713		
Total	47	0.0326738				

Unusual Observations for Ra

Obs	StdOrder	Ra	Fit	SEFit	Residual	StResid
3	3	0.136	0.076	0.013799	0.06	3.07R
20	20	0.076	0.036667	0.013799	0.039333	2.02R
41	41	0.106	0.053	0.013799	0.053	2.72R

R denotes an observation with a large standardized residual

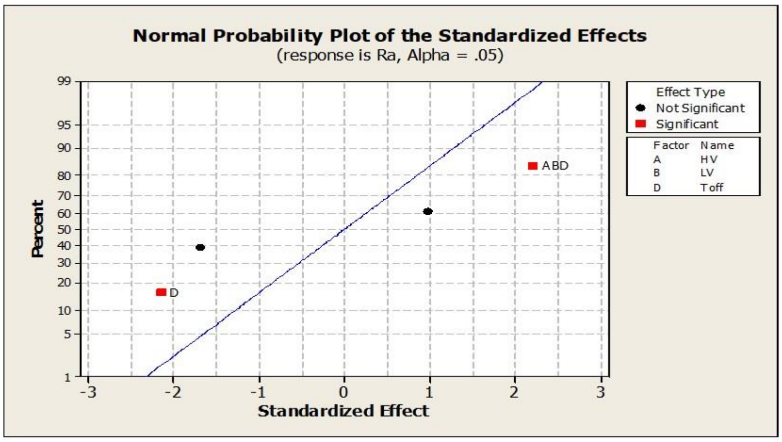

Figure A25. Normal probability plot of the standardized effects of Ra for Ti6Al4V considering all factors.

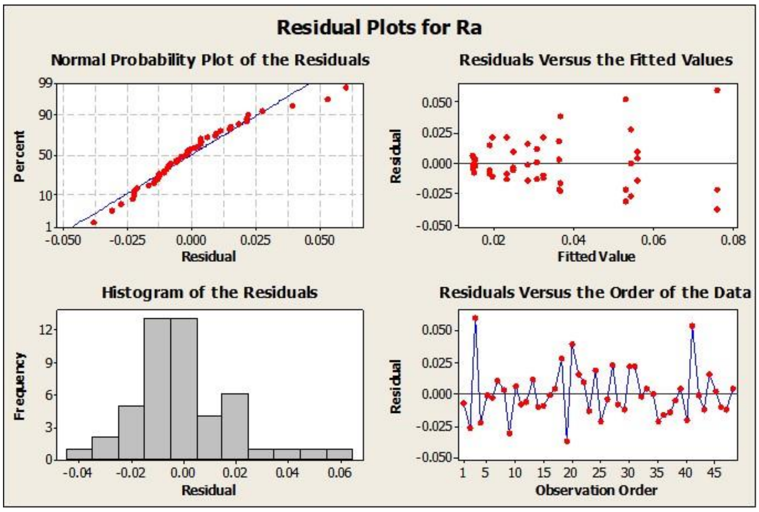

Figure A26. Residual plot of Ra for Ti6Al4V considering all factors.

The p-values from the ANOVA table in Table A10 of the refitted MODEL indicate that the models as well as these factors are significant.

Table A10. ANOVA table of Ra for Ti6Al4V considering significant factors.

Factorial Fit: Ra versus HV, LV, T_{OFF}					
Estimated Effects and Coefficients for Ra (coded units)					
Term Effect	Coef	SE	Coef	T	P
Constant		0.033438	0.003477	9.62	0
HV	−0.011708	−0.005854	0.003477	−1.68	0.099
LV	0.006792	0.003396	0.003477	0.98	0.334
T_{OFF}	−0.014958	−0.007479	0.003477	−2.15	0.037
HV*LV*T_{OFF}	0.015375	0.007688	0.003477	2.21	0.032
S = 0.0240897	R−Sq = 23.63%	R−Sq(adj) = 16.52%			

Continued on next page

Factorial Fit: Ra versus HV, LV, T_{OFF}

Analysis of Variance for Ra (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	3	0.004884	0.004884	0.0016279	2.81	0.051
3-Way	1	0.002837	0.002837	0.0028367	4.89	0.032
Residual	43	0.024954	0.024954	0.0005803		
Lack of Fit	3	0.003549	0.003549	0.0011831	2.21	0.102
Pure	40	0.021404	0.021404	0.0005351		
Total	47	0.032674				

Unusual Observations for Ra

Obs	StdOrder	Ra	Fit	SEFit	Residual	StResid
3	3	0.136	0.054208	0.007408	0.081792	3.57R
41	41	0.106	0.025651	0.00717	0.080349	3.49R

R denotes an observation with a large standardized residual.

Estimated Coefficients for Ra using data in uncoded units

Term	Coef
Constant	0.022132
HV	0.0728368
LV	0.00161593
T_{OFF}	−0.00644936
HV*LV*T_{OFF}	−4.25E-04

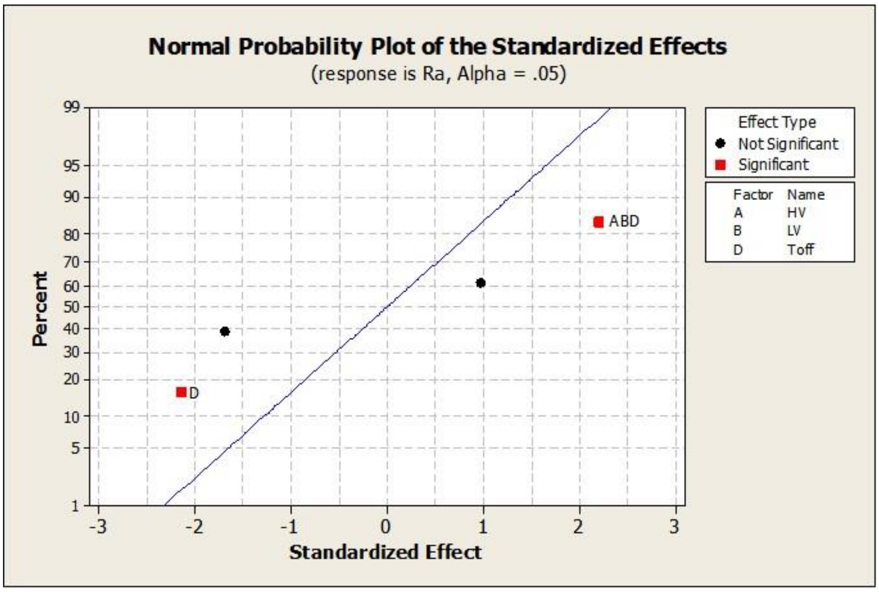

Figure A27. Normal probability plot of the standardized effects of Ra for Ti6Al4V considering significant factors.

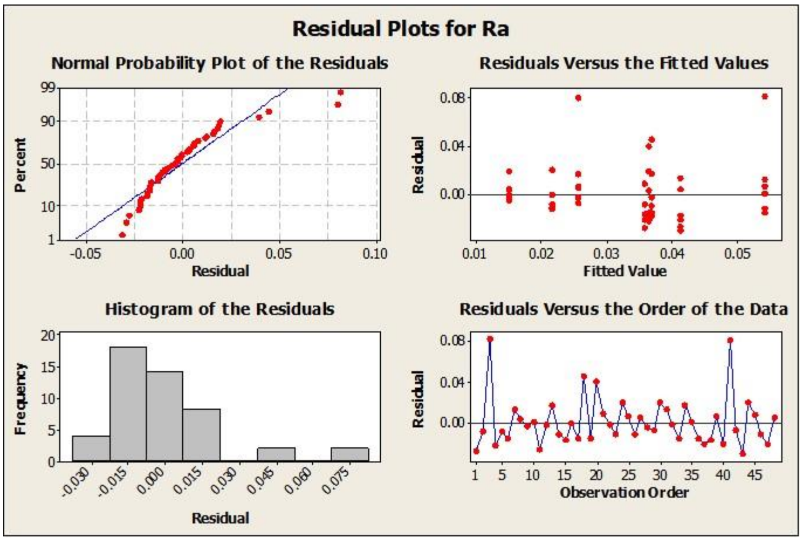

Figure A28. Residual plot of Ra for Ti6Al4V considering all factors.

After developing the ANOVA tables for significant factors the Main Effects Plot in Figure A29 as well as the Interaction Plot in Figure A30 is prepared for Ra. The main effects plot shows steep slope of means indicating the significance of these factors. The interaction plot in Figure A30 shows non parallel lines of significance.

Next, the optimized values of significant factors are to be calculated. For optimization of Surface Roughness we have set the Target Value to ‘0’ while the Upper Value to ‘0.007’ which is the Minimum value of Surface Roughness and then the value of Desirability functions is evaluated.

d = 0 emphasizes that y or response is more away from the target that is “Less emphasis on the Target”, because the target was taken as “0” and response comes out to be far away from it (rather far from the Upper value that was taken as 0.007). It could have been d = 1 or close to 1, if the target was set close to 0.01 and upper value was taken as greater than say 0.03.

The Optimized value for HV is 0.70 V, LV is 30 A and T_{OFF} is 6.5 µs for these values minimum Ra is 0.009 mm (Figure A31).

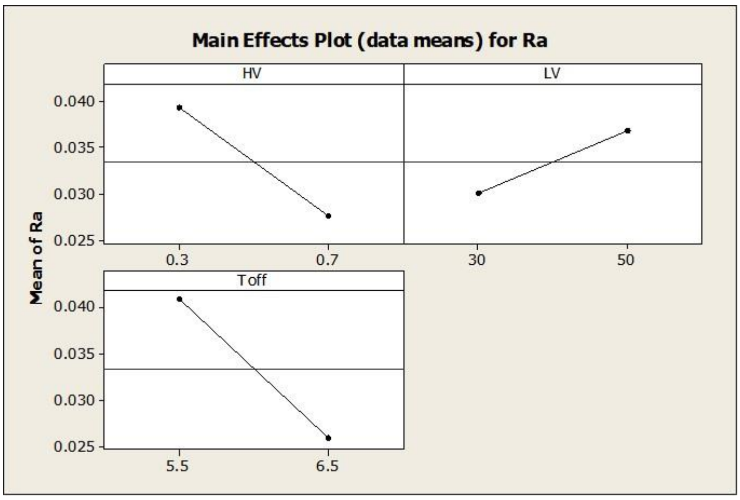

Figure A29. Main effects plot of Ra for Ti6Al4V considering significant factors.

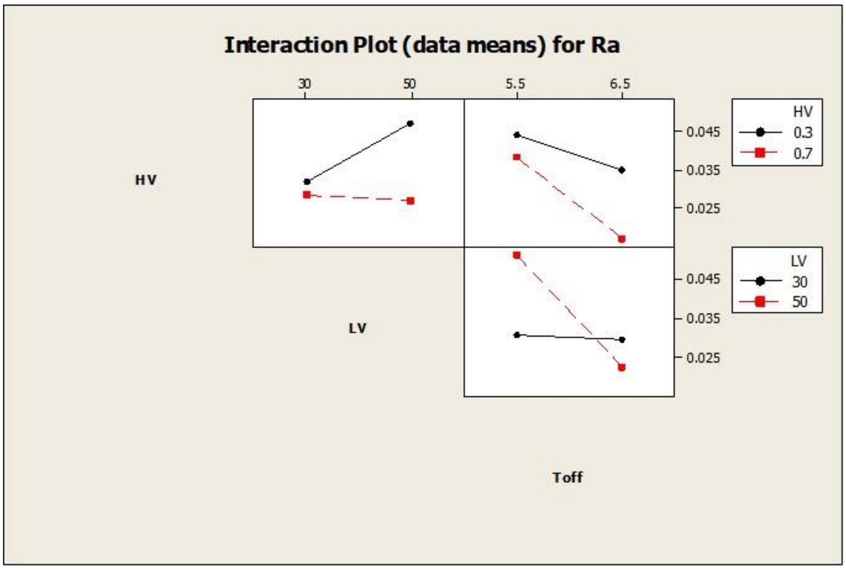

Figure A30. Residual plot of Ra for Ti6Al4V considering T_{ON} & LV.

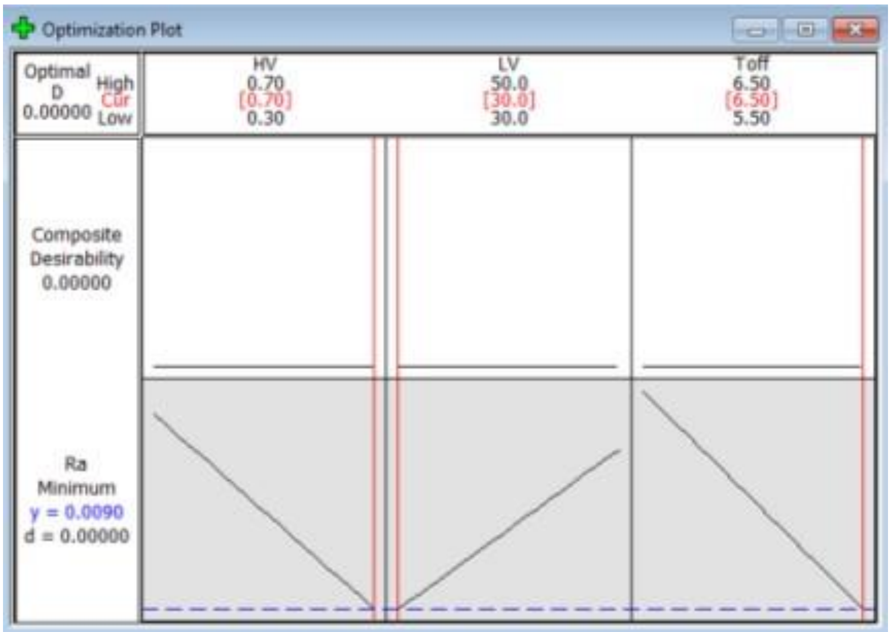

Figure A31. Optimization plot of Ra for Ti6Al4V for significant factors.

Appendix 3.5. Analysis of results of base radius (R) for Ti6Al4V

The ANOVA table in Table A11 as well as the Normal Probability Plot in Figure A32 indicates that T_{ON} is significant factors when considering R for Ti6Al4V. Now, the model is refitted by eliminating the non significant values and considering only T_{ON} as an input factor.

Table A11. ANOVA table of R for Ti6Al4V considering all factors.

Factorial Fit: R versus HV, LV, T_{ON}, T_{OFF}

Estimated Effects and Coefficients for R (coded units)

Term Effect	Coef	SE	Coef	T	P
Constant		1.46094	0.02688	54.34	0
HV	0.03171	0.01585	0.02688	0.59	0.56
LV	−0.02596	−0.01298	0.02688	−0.48	0.633
T_{ON}	0.17746	0.08873	0.02688	3.3	0.002
T_{OFF}	0.01138	0.00569	0.02688	0.21	0.834
HV*LV	0.01304	0.00652	0.02688	0.24	0.81
HV*T_{ON}	−0.04021	−0.0201	0.02688	−0.75	0.46
HV*T_{OFF}	0.02354	0.01177	0.02688	0.44	0.664
LV*T_{ON}	−0.01421	−0.0071	0.02688	−0.26	0.793
LV*T_{OFF}	0.03154	0.01577	0.02688	0.59	0.562
T_{ON}*T_{OFF}	−0.02738	−0.01369	0.02688	−0.51	0.614
HV*LV*T_{ON}	−0.03404	−0.01702	0.02688	−0.63	0.531
HV*LV*T_{OFF}	−0.00113	−0.00056	0.02688	−0.02	0.983
HV*T_{ON}*T_{OFF}	−0.00671	−0.00335	0.02688	−0.12	0.901
LV*T_{ON}*T_{OFF}	−0.00271	−0.00135	0.02688	−0.05	0.96
HV*LV*T_{ON}*T_{OFF}	0.00312	0.00156	0.02688	0.06	0.954
S = 0.186260	R−Sq = 29.55%	R−Sq(adj) = 0.00%			

Analysis of Variance for R (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
MainEffects	4	0.3996	0.3996	0.0999003	2.88	0.038
2-Way Interactions	6	0.05145	0.05145	0.0085743	0.25	0.957
3-Way Interactions	4	0.01455	0.01455	0.0036373	0.1	0.98
4-Way Interactions	1	0.00012	0.00012	0.0001172	0	0.954
Residual Error	32	1.11017	1.11017	0.0346929		
Pure Error	32	1.11017	1.11017	0.0346929		
Total	47	1.57589				

Unusual Observations for R

Obs	StdOrder	R	Fit	SE Fit	Residual	StResid
17	17	1.069	1.38067	0.10754	−0.31167	−2.05R
18	18	0.98	1.371	0.10754	−0.391	−2.57R
20	20	1.01	1.37633	0.10754	−0.36633	−2.41R

R denotes an observation with a large standardized residual.

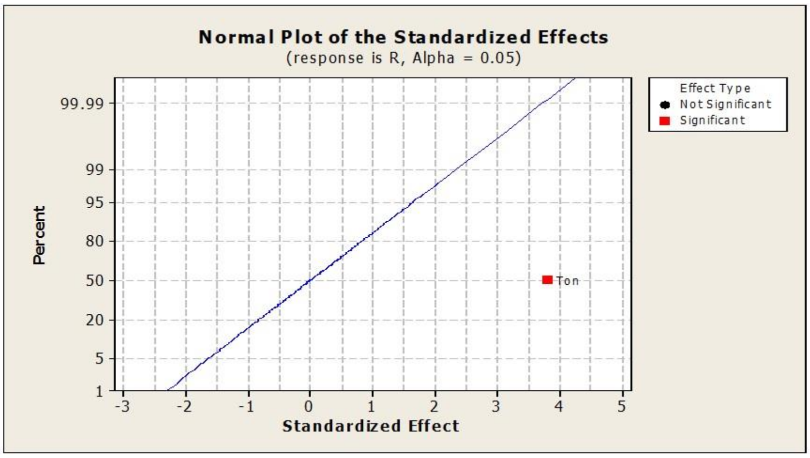

Figure A32. Normal probability plot of the standardized effects of R for Ti6Al4V considering all factors.

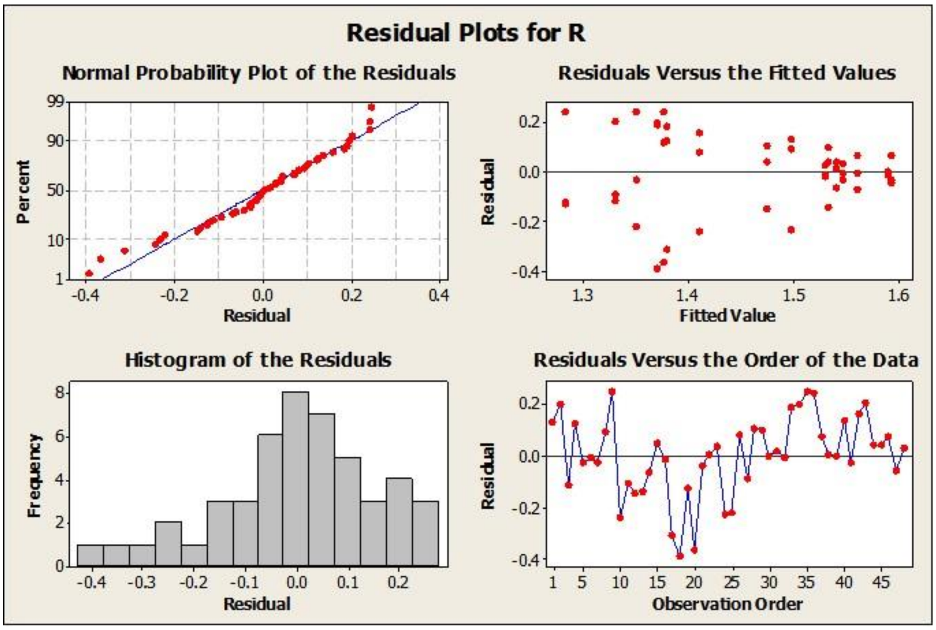

Figure A33. Residual plot of R for Ti6Al4V considering all factors.

The p-values from the ANOVA table in Table A12 of the refitted MODEL indicate that the models as well as these factors are significant.

Table A12. ANOVA table of R for Ti6Al4V considering significant factors.

Factorial Fit: R versus T_{ON}						
Estimated Effects and Coefficients for R (coded units)						
Term Effect	Coef	SE		Coef	T	P
Constant		1.46094		0.02329	62.72	0
T_{ON}	0.17746	0.08873		0.02329	3.81	0
S = 0.161379	R−Sq = 23.98%	R−Sq(adj) = 22.33%				
Analysis of Variance for R (coded units)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main	1	0.3779	0.3779	0.3779	14.51	0
Residual	46	1.198	1.198	0.02604		
Pure	46	1.198	1.198	0.02604		
Total	47	1.5759				
Unusual Observations for R						
Obs	StdOrder	R	Fit	SE Fit	Residual	StResid
18	18	0.98	1.37221	0.03294	−0.39221	−2.48R
20	20	1.01	1.37221	0.03294	−0.36221	−2.29R
R denotes an observation with a large standardized residual.						
Estimated Coefficients for R using data in uncoded units.						

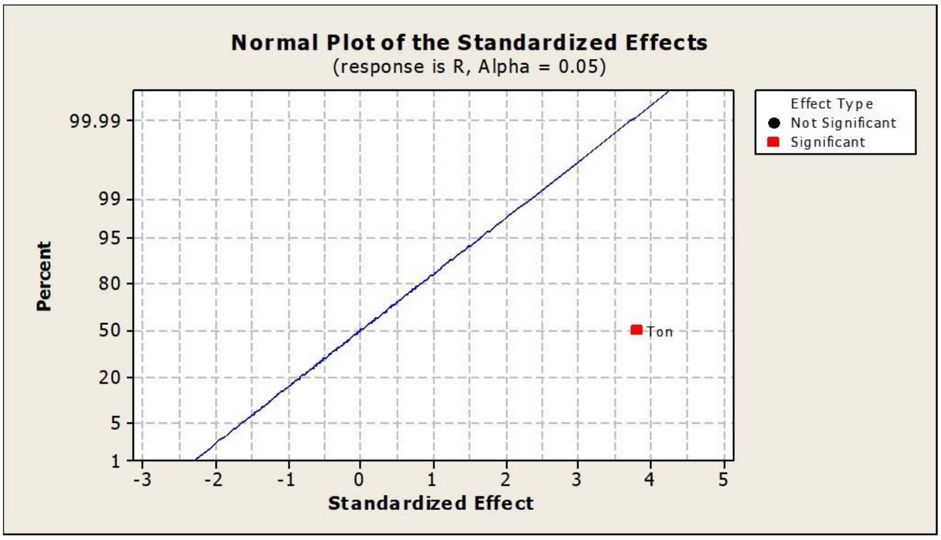

Figure A34. Normal probability plot of the standardized effects of R for Ti6Al4V considering significant factors.

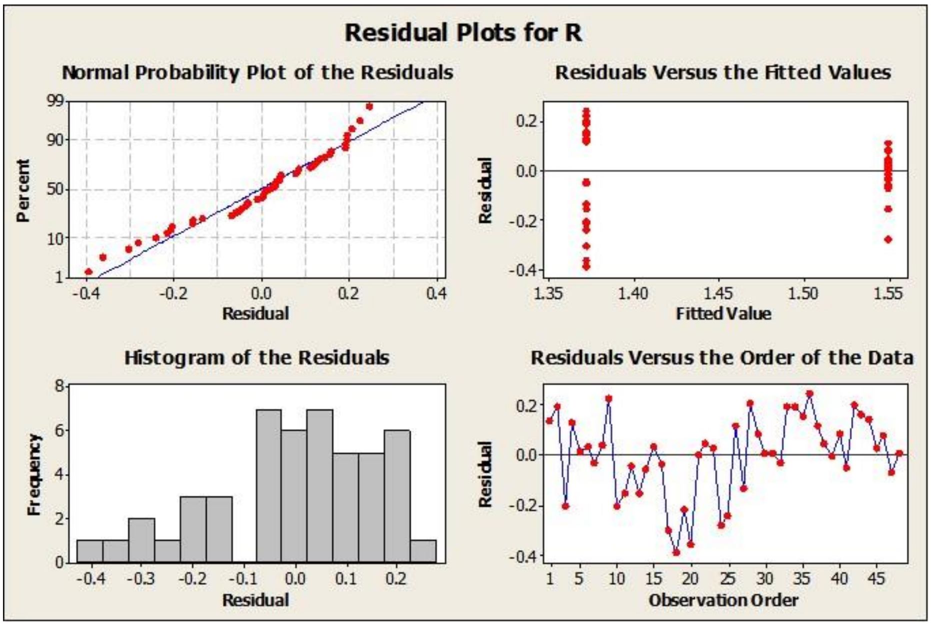

Figure A35. Residual plot of R for Ti6Al4V considering all factors.

After developing the ANOVA tables for significant factors the Main Effects Plot in Figure A36 as well as the Interaction Plot in Figure A37 is prepared for R. The main effects plot shows steep slope of means indicating the significance of these factors. The interaction plot shows near parallel lines of non significance between T_{ON} & LV.

Next, the optimized values of significant factors are to be calculated. For optimization of Base Radius value, we have set the Target Value to '1.5' while the Upper & Lower Values to 1.55 & 1.45 respectively and then the value of Desirability functions is evaluated. The Weight of Specific Desirability Function (d) equals to 1 i.e. emphasis on the Target. The Desirability for a Response increases linearly.

The Optimized value for T_{ON} is 5.8003 for the optimized Rvalue of 1.5 mm (Figure A38).

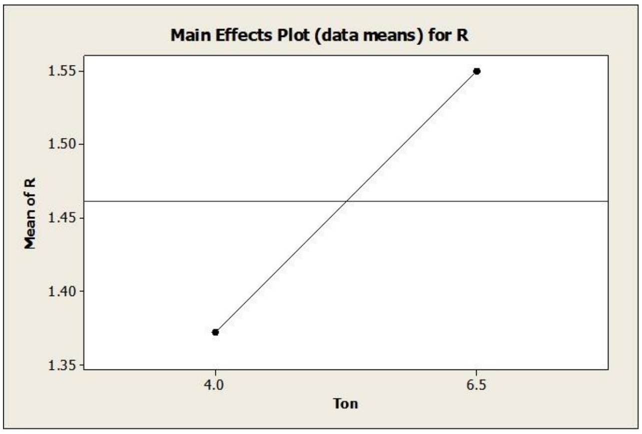

Figure A36. Main effects plot of R for Ti6Al4V considering significant factors.

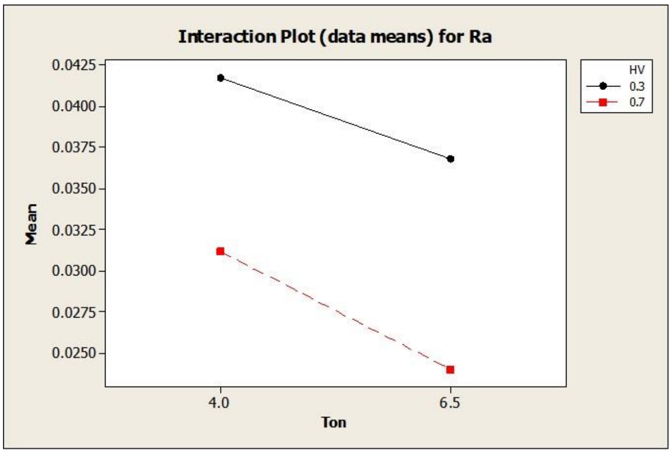

Figure A37. Residual plot of R for Ti6Al4V considering T_{ON} & LV.

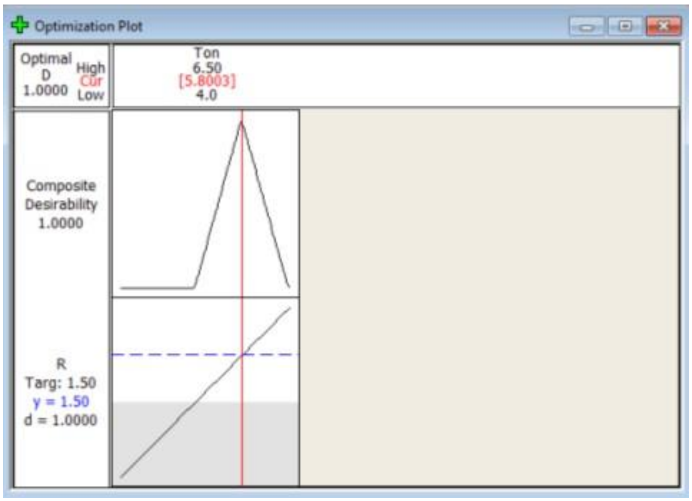

Figure A38. Optimization plot of R for Ti6Al4V for significant factors.

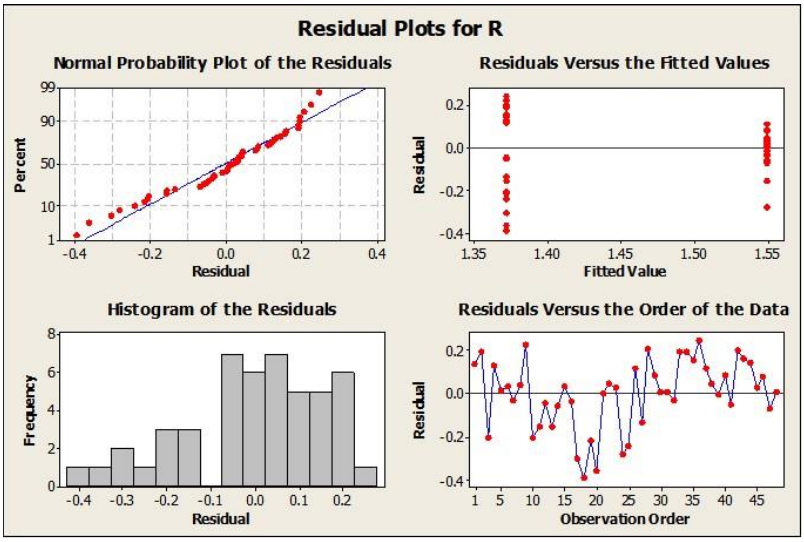

Figure A39. Residual plot of R for Ti6Al4V considering all factors.

Appendix 4

Appendix 4.1. Regression for Ti6Al4V

Firstly, a matrix plot is prepared considering all responses and all factors for initial experiments carried out on Ti6Al4V (Figures A40–A45).

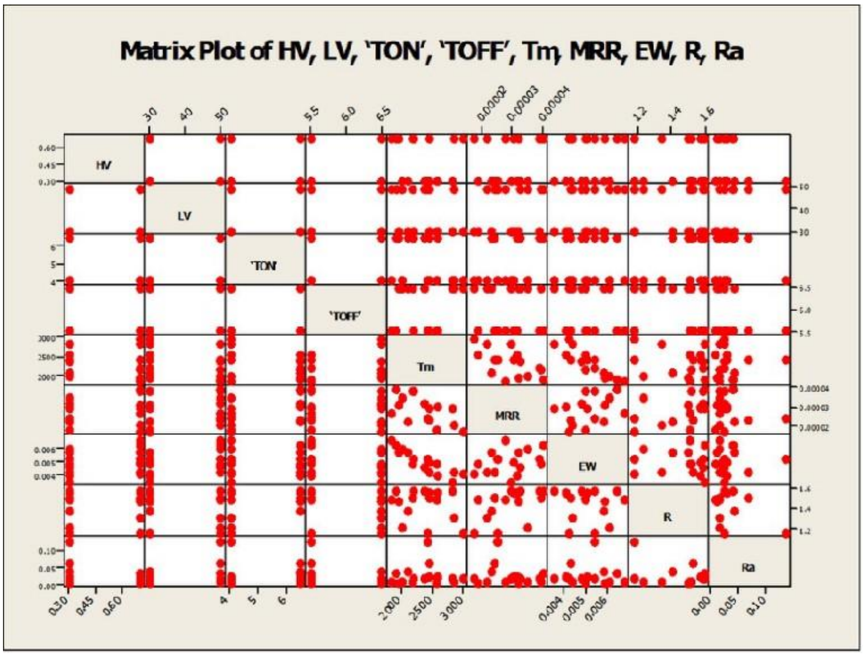

Figure A40. Matrix plot of all factors as well as all responses for Ti6Al4V.

This plot shows scattered responses which shows normal relationship. Now, the Matrix Plot for individual responses is prepared.

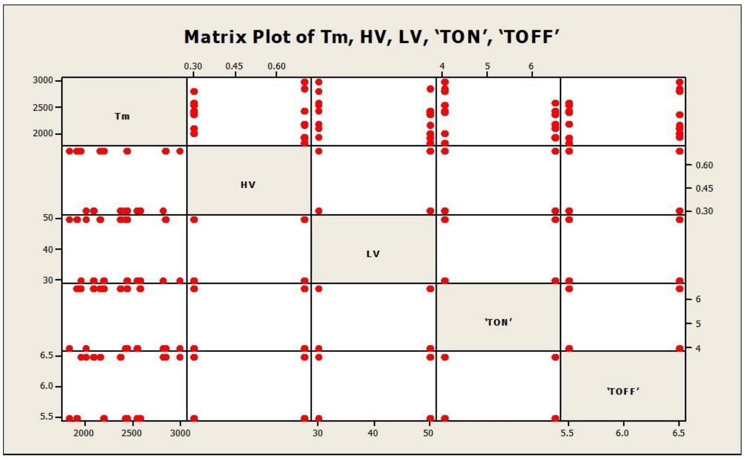

Figure A41. Matrix plot of Tm with HV, LV, T_{ON} and T_{OFF} for Ti6Al4V.

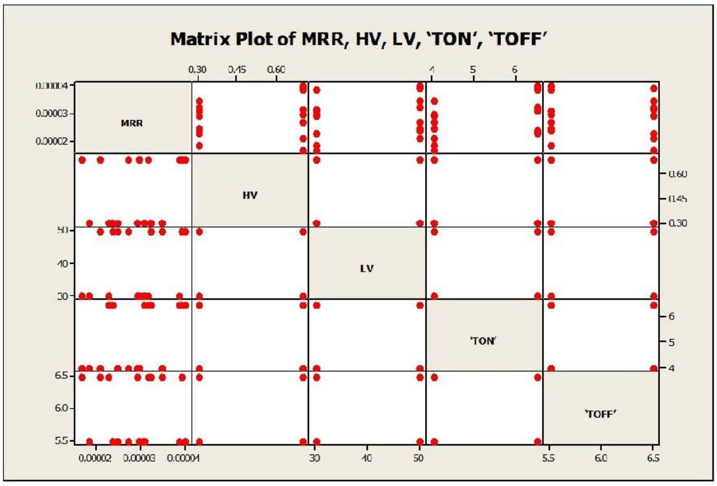

Figure A42. Matrix plot of MRR with HV, LV, T_{ON} and T_{OFF} for Ti6Al4V.

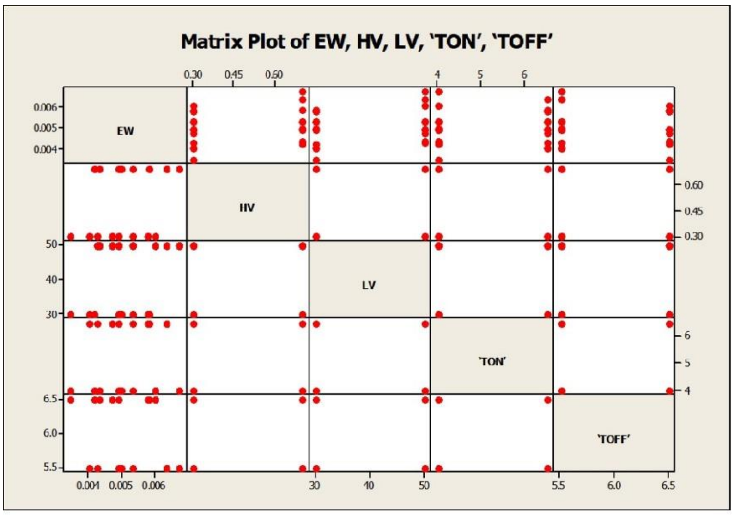

Figure A43. Matrix plot of EW with HV, LV, T_{ON} and T_{OFF} for Ti6Al4V.

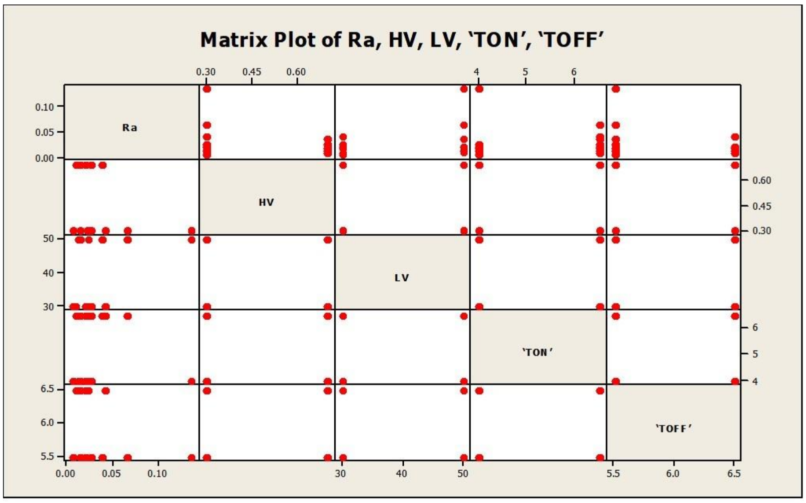

Figure A44. Matrix plot of Ra with HV, LV, T_{ON} and T_{OFF} for Ti6Al4V.

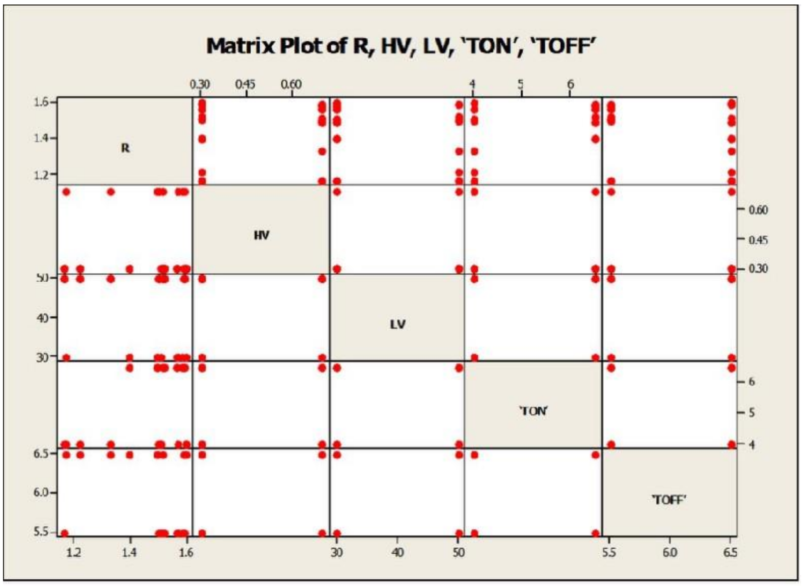

Figure A45. Matrix plot of R with HV, LV, T_{ON} and T_{OFF} for Ti6Al4V.

All these individual response plots are bi variate because we have considered a two level experiment. Now the best subsets regression is run with all predictors listed to find the best combination of R^2, adjusted R^2, Mallows' Cp, S and number of predictors.

Appendix 4.2. Regression for Tm on Ti6Al4V

Consider the two predictor model which has highest adjusted R^2, lowest Mallows' Cp, and lowest S values which shows that LV and Pulse ON Time has significant effect on Tm. Also, the single predictor model with Cp = 1.3 can be considered but since both the models have T_{ON} as a common significant predictor, its better to consider a two predictor model (Table A13).

Table A13. Best subsets regression table for Tm vs all predictors for Ti6Al4V.

Variables	R-Sq	R-Sq(adj)	Cp	S	HV	LV	T_{ON}	T_{OFF}
1	16.3	10.3	1.3	334.50	×			
1	8.8	2.2	2.5	349.19		×		
2	25.1	13.5	1.9	328.45	×	×		
2	19.3	6.9	2.8	340.84		×	×	
3	28.1	10.1	3.4	334.94	×	×	×	
3	27.7	9.6	3.5	335.83	×		×	×
4	30.7	5.5	5.0	343.40	×	×	×	×

Next, the regression model is run for Tm with all the factors.

This model in Table A14 indicates that there is no significant factor for R as the p-value of all the factors is greater than 0.05. But considering the least p-value i.e. for T_{ON}; $p = 0.104$, the remaining predictors are removed from the model. The Variance Inflation Factor (VIF) = 1.006 shows that there exists no correlation between the predictors.

Table A14. Regression model for Tm of Ti6Al4V with all the factors.

Regression Analysis: Tm versus HV, LV, 'T_{ON}', 'T_{OFF}'					
Weighted analysis using weights in Tm					
The regression equation is Tm = 2693 − 233 HV − 9.69 LV − 121 'T_{ON}' + 138 'T_{OFF}'					
Predictor Coef	SE	Coef	T	P	VIF
Constant	2693	1150	2.34	0.039	
HV	−232.7	424.3	−0.55	0.594	1.005
LV	−9.685	8.479	−1.14	0.278	1.002
'T_{ON}'	−120.52	68.02	−1.77	0.104	1.006
'T_{OFF}'	138.2	169.8	0.81	0.433	1.007
S = 16412.0	R−Sq = 33.7%	R−Sq(adj) = 9.6%			
Analysis of Variance					
Source	DF	SS	MS	F	P
Regression	4	1505291848	376322962	1.4	0.298
ResidualError	11	2962887114	269353374		
Total	15	4468178962			
Source	DF	Seq SS			
HV	1	47673236			
LV	1	392065717			
'T_{ON}'	1	887274744			
'T_{OFF}'	1	178278151			

The regression model is now re-run omitting the non-significant factors i.e. only T_{ON} is considered as a predictor and the following analysis is obtained in Table A15.

Table A15. Regression model for Tm of Ti6Al4V with significant predictors.

Regression Analysis: Tm versus 'T_{ON}'						
Weighted analysis using weights in Tm						
The regression equation is Tm = 3050 − 125 'T_{ON}'						
Predictor Coef		SE	Coef	T	P	VIF
Constant		3049.5	350.3	8.71	0.000	
'T_{ON}'		−125.21	65.78	−1.90	0.078	1.000
S = 15923.2		R−Sq = 20.6%	R−Sq(adj) = 14.9%			
Analysis of Variance						
Source		DF	SS	MS	F	P
Regression		1	918486870	918486870	3.62	0.078
Residual Error		14	3549692092	253549435		
Total		15	4468178962			
Unusual Observations						
Obs	'T_{ON}'	Tm	Fit	SE Fit	Residual	StResid
4	4	1831	2549	113	−718	−2.02R
R denotes an observation with a large standardized residual.						

The regression equation shows negative sign prior to T_{ON} which means that higher the T_{ON} lesser the Tm. Also, from the value of R-Sq (adj), the Pulse ON Time predictor accounts for **14.9%** of the total variation calculated from regression equation.

Now, the residuals are analyzed for the validation of assumptions of Regression Analysis.

The residual plots in Figures A46 and A47 for Tm show that residuals are Normally Distributed, show equal variance, are independent of each other and also confirm that one or two points do not overly influence the model.

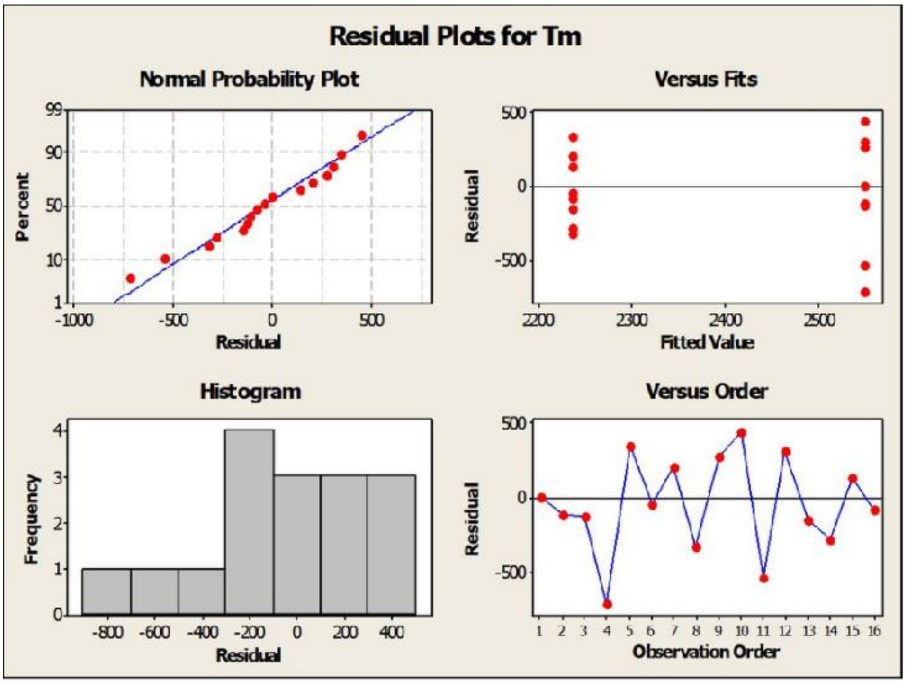

Figure A46. Residual plots for Tm with T_{ON} as a predictor for Ti6Al4V.

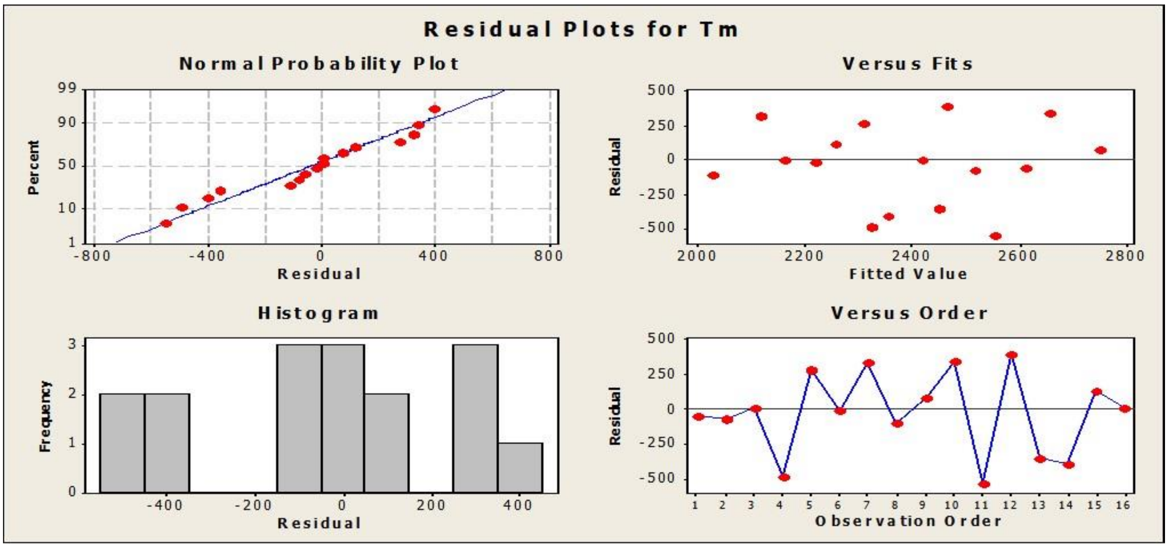

Figure A47. Residual plots for Tm with all predictors for Ti6Al4V.

Appendix 4.2. Regression for MRR on Ti6Al4V

Consider the two predictor model which has highest adjusted R^2, lowest Mallows' Cp, and lowest S values which shows that HV and Pulse ON Time has significant effect on Tm. Also, the single predictor model with Cp = 0.9 can be considered but since both the models have T_{ON} as a common significant predictor, its better to consider a two predictor model (Table A16).

Table A16. Best subsets regression table for MRR vs all predictors for Ti6Al4V.

Variables	R-Sq	R-Sq(adj)	C_p	S	HV	LV	'T_{ON}'	'T_{OFF}'
1	26.1	20.9	0.9	6.48E-06	×			
1	5.9	0	4.5	7.32E-06		×		
2	32	21.6	1.9	6.46E-06	×	×		
2	31	20.3	2.1	6.51E-06		×	×	
3	36.8	21.1	3	6.48E-06	×	×	×	
3	32.3	15.3	3.8	6.71E-06	×		×	×
4	37.1	14.2	5	6.75E-06	×	×	×	×

Next, the regression model is run for Tm with all the factors.

This model in Table A17 indicates that T_{ON} is nearly significant as its p-value is 0.052 while the remaining are greater than 0.05. A positive sign on the T_{ON} in the regression equation shows that increase of T_{ON} can be significant. The Variance Inflation Factor (VIF) = 1.006 shows that there exists no correlation between the predictors.

Table A17. Regression Model for MRR of Ti6Al4V with all the factors.

Regression Analysis: MRR versus HV, LV, ‘T_{ON}’, ‘T_{OFF}’					
Weighted analysis using weights in Tm					
The regression equation is					
MRR = 0.000010 + 0.000007 HV + 0.000000 LV + 0.000003 ‘T_{ON}’ − 0.000001 ‘T_{OFF}’					
Coefficients and Statistics:					
Predictor	Coef	SE Coef	T	P	VIF
Constant	9.53E-06	2.33E-05	0.41	0.691	
HV	7.06E-06	8.61E-06	0.82	0.43	1.005
LV	1.3E-07	1.7E-07	0.76	0.464	1.002
‘T_{ON}’	0.000003	1.38E-06	2.18	0.052	1.006
‘T_{OFF}’	−9E-07	3.45E-06	−0.26	0.798	1.007
Model Summary:					
S (Standard Error): 0.000333005					
R-Sq: 35.7%					
R-Sq (adj): 12.3%					
Analysis of Variance:					
Source	DF	SS	MS	F	P
Regression	4	6.77E-07	1.69E-07	1.53	0.262
Residual	11	1.22E-06	1.11E-07		
Total	15	1.90E-06			
Sequential Sums of Squares:					
Source	DF	Seq SS			
HV	1	5.59E-08			
LV	1	8.03E-08			
‘T_{ON}’	1	5.33E-07			
‘T_{OFF}’	1	7.61E-09			

The regression model is now re-run omitting the non significant factors i.e. only T_{ON} is considered as a predictor and the following analysis is obtained:

The regression equation in Table A18 shows positive sign prior to T_{ON} which means that higher the T_{ON}, the higher the MRR. Also, from the value of R-sq (adj), the Pulse ON Time predictor accounts for **23%** of the total variation calculated from regression equation. It means that as a result of regression analysis, T_{ON} is the significant predictor for MRR.

Table A18. Regression Model for MRR of Ti6Al4V with significant predictors.

Regression Analysis: MRR versus ‘T_{ON}’					
Weighted analysis using weights in Tm					
The regression equation is					
MRR = 0.000013 + 0.000003 ‘TON’					
Predictor	Coef	SE Coef	T	P	VIF
Constant	1.27E-05	6.86E-06	1.85	0.086	
‘TON’	3.02E-06	1.29E-06	2.34	0.034	1

Continued on next page

Regression Analysis: MRR versus ‘T_{ON}’					
Model Summary:					
S (Standard Error): 0.000311950					
R-Sq: 28.2%					
R-Sq (adj): 23.0%					
Analysis of Variance:					
Source	DF	SS	MS	F	P
Regression	1	5.34E-07	5.34E-07	5.49	0.034
Residual	14	1.36E-06	9.73E-08		
Total	15	1.90E-06			

Now, the residuals are analyzed for the validation of assumptions of Regression Analysis.

The residual plots for MRR in Figures A48 and A49 show that residuals are Normally Distributed, show equal variance, are independent of each other and also confirm that one or two points do not overly influence the model.

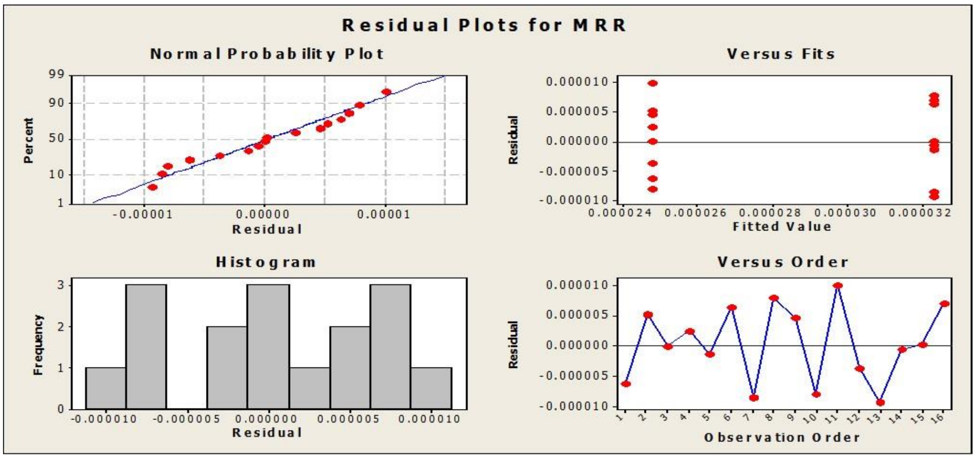

Figure A48. Residual plots for MRR with T_{ON} as a predictor for Ti6Al4V.

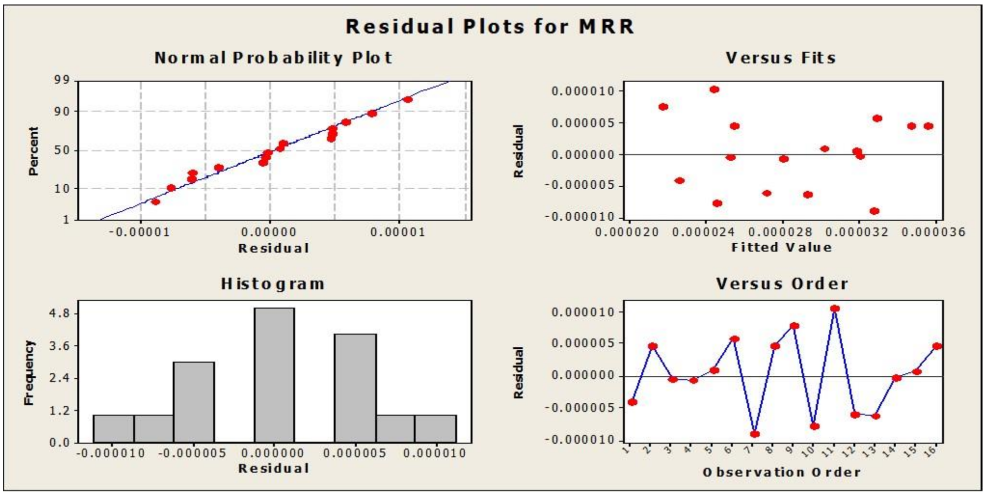

Figure A49. Residual plots for MRR with all predictors for Ti6Al4V.

Appendix 4.3. Regression for EWR on Ti6Al4V

Consider the two predictor model which has highest adjusted R^2, lowest Mallows' Cp, and lowest S values which shows that HV and Pulse ON Time has significant effect on Tm. Also, the single predictor models with Cp = 0.8 can be considered but since both the models have T_{ON} and LV singly, its better to consider a two predictor model. Next, the regression model in Table A19 is run for EWR with all the factors.

Table A19. Best subsets regression table for EW vs all predictors for Ti6Al4V.

Vars	R-Sq	R-Sq(adj)	C_p	S	HV	LV	'T_{ON}'	'T_{OFF}'
1	8.8	2.3	0.8	0.000895	×			
1	8.5	2	0.8	0.000897		×		
2	17.3	4.6	1.6	0.000885	×	×		
2	12.4	0	2.3	0.000911	×			×
3	21	1.2	3.1	0.0009	×	×		×
3	18.1	0	3.5	0.000917	×		×	×
4	21.7	0	5	0.000936	×	×	×	×

Table A20. Regression Model for EW of Ti6Al4V with all the factors.

Regression Analysis: EW versus HV, LV, 'T_{ON}', 'T_{OFF}'

Weighted analysis using weights in Tm

EW = 0.00534 + 0.00123 HV + 0.000025 LV + 0.000079 'T_{ON}'−0.000395 'T_{OFF}'

Predictor	Coef	SE Coef	T	P	VIF
Constant	0.005339	0.00311	1.72	0.114	
HV	0.001229	0.001148	1.07	0.307	1.005
LV	2.51E-05	2.29E-05	1.1	0.297	1.002
'T_{ON}'	7.85E-05	0.000184	0.43	0.678	1.006
'T_{OFF}'	−0.00039	0.000459	−0.86	0.408	1.007

Model Summary:

S (Standard Error): 0.0443962

R^2: 22.4%

R^2 (adj): 0.0%

Analysis of Variance:

Source	DF	SS	MS	F	P
Regression	4	0.006245	0.001561	0.79	0.554
Residual	11	0.021681	0.001971		
Total	15	0.027927			

Sequential Sum of Squares:

Source	DF	Seq SS
HV	1	0.001974
LV	1	0.002378
'T_{ON}'	1	0.000437
'T_{OFF}'	1	0.001457

This model in Table A20 indicates that there is no significant factor for EW so no need to rerun the model.

Now, the residuals are analyzed for the validation of assumptions of Regression Analysis.

The residual plots for EWR in Figure A50 also confirm that one or two points do not overly influence the model.

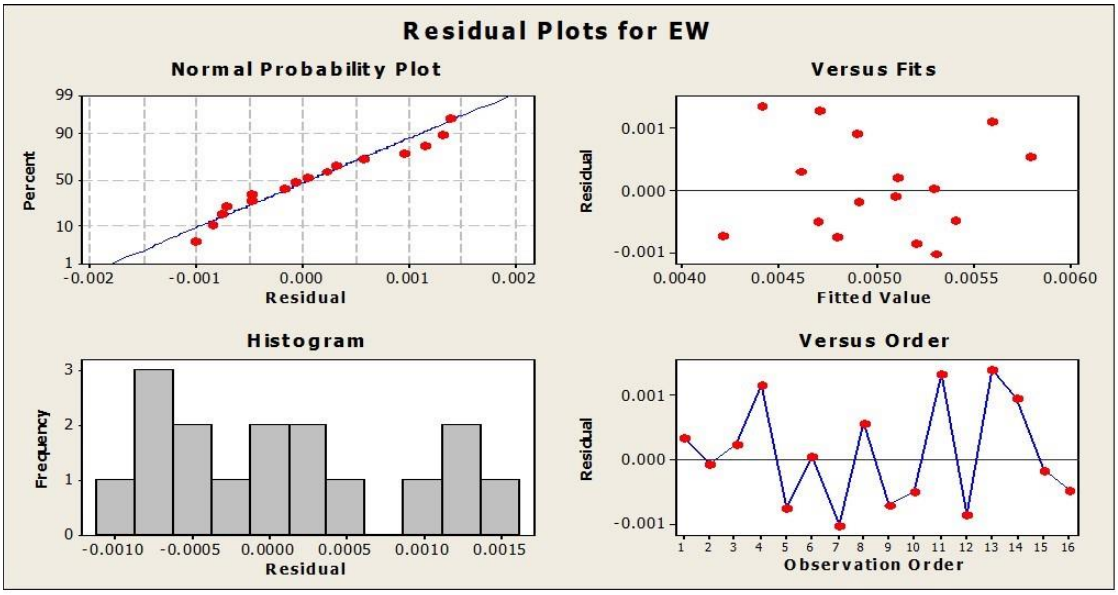

Figure A50. Residual plots for EWR with all predictors for Ti6Al4V.

Appendix 4.4. Regression for Ra on Ti6Al4V

Consider the three predictor model which has highest adjusted R^2, lowest Mallows’ Cp, and lowest S values which shows that HV, LV and Pulse OFF Time has significant effect on Tm (Table A21). Next, the regression model in Table A22 is run for Tm with all the factors.

Table A21. Best subsets regression table for Ra vs all predictors for Ti6Al4V.

Vars	R-Sq	R-Sq (adj)	Cp	S	HV	LV	‘T_{ON}’	‘T_{OFF}’
1	13.3	7.1	2.7	0.030543				×
1	13.3	7.1	2.7	0.030543	×			
2	26.6	15.3	2.5	0.029165	×			×
2	21.8	9.7	3.3	0.030105		×		×
3	35.1	18.8	3	0.028548	×	×		
3	26.7	8.3	4.4	0.030341	×		×	×
4	35.1	11.6	5	0.029801	×	×	×	×

Table A22. Regression model for Ra of Ti6Al4V with all the factors.

Regression Analysis: Ra versus HV, LV, ‘T_{ON}’, ‘T_{OFF}’						
Weighted analysis using weights in Tm						
The regression equation is						
Ra = 0.162−0.0529 HV + 0.000991 LV−0.00158 ‘T_{ON}’−0.0225 ‘T_{OFF}’						
Predictor	Coef	SE Coef	T	P	VIF	
Constant	0.1618	0.1015	1.59	0.139		
HV	−0.05287	0.03747	−1.41	0.186	1.005	
LV	0.000991	0.000749	1.32	0.213	1.002	
‘T_{ON}’	−0.00158	0.006007	−0.26	0.798	1.006	
‘T_{OFF}’	−0.02254	0.015	−1.5	0.161	1.007	
Statistic	Value					
S	1.4493					
R-Sq	36.00%					
R-Sq(adj)	12.70%					
Source	DF	SS	MS	F	P	
Regression	4	12.992	3.248	1.55	0.256	
Residual Error	11	23.105	2.1			
Total	15	36.097				
Analysis of Variance						
Source	DF	Seq SS				
HV	1	4.711				
LV	1	3.46				
‘T_{ON}’	1	0.074				
‘T_{OFF}’	1	4.747				
Unusual Observations						
Obs	HV	Ra	Fit	SE Fit	Residual	St Resid
3	0.3	0.136	0.065	0.017	0.071	2.95R
R denotes an observation with a large standardized residual.						

This model in Table A22 indicates that there is no significant factor for EW so no need to rerun the model. Now, the residuals are analyzed for the validation of assumptions of Regression Analysis.

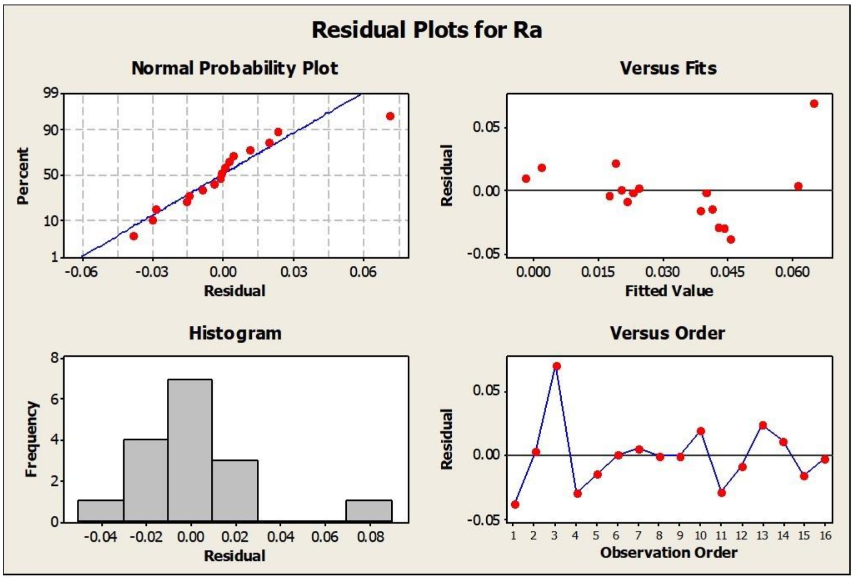

Figure A51. Residual plots for Ra with all predictors for Ti6Al4V.

Appendix 4.5. Regression for R on Ti6Al4V

Consider the two predictor model which has highest adjusted R^2, lowest Mallows' Cp, and lowest S values which shows that HV and Pulse ON Time has significant effect on Tm. Also, the single predictor models with Cp = 1.3 can be considered but since both the models have T_{ON} and T_{OFF} as a common predictor, its better to consider a two predictor model.

Next, the regression model in Table A23 is run for R with all the factors.

Table A23. Best subsets regression table for R vs all predictors for Ti6Al4V.

Vars	R-Sq	R-Sq (adj)	Mallows C_p	S	HV	LV	'T_{ON}'	'T_{OFF}'
1	25.3	19.9	1.3	0.13748	×			
1	8.7	2.2	4.3	0.15196		×		
2	34	23.9	1.8	0.13409	×	×		
2	28.9	18	2.7	0.13917	×		×	
3	37.6	22	3.1	0.13568	×	×	×	
3	34.7	18.3	3.6	0.13887	×		×	×
4	38.3	15.8	5	0.14096	×	×	×	×

This model in Table A24 indicates that there is no significant factor for R as the p-value of all the factors is greater than 0.05. But considering the least p-value i.e. for T_{ON}; p = 0.064, the remaining predictors are removed from the model. The Variance Inflation Factor (VIF) = 1.006 shows that there exists no correlation between the predictors.

Table A24. Regression model for R of Ti6Al4V with all the factors.

Regression Analysis: R versus HV, LV, 'T_{ON}', 'T_{OFF}'						
Weighted analysis using weights in Tm. The regression equation is:						
R = 1.74 + 0.014 HV−0.00310 LV + 0.0608 'T_{ON}'–0.0810 'T_{OFF}'						
Predictor	Coef	SE Coef		T	P	VIF
Constant	1.7388	0.5002		3.48	0.005	
HV	0.0144	0.1846		0.08	0.939	1.005
LV	−0.0031	0.00369		−0.84	0.418	1.002
'T_{ON}'	0.06084	0.0296		2.06	0.064	1.006
'T_{OFF}'	−0.08095	0.0739		−1.1	0.297	1.007
S = 7.14180	R−Sq = 36.3%		R−Sq(adj) = 13.1%			
Analysis of Variance						
Source	DF	SS		MS	F	P
Regression	4	319.7		79.92	1.57	0.251
Residual Error	11	561.06		51.01		
Total	15	880.76				
Source	DF	Seq SS				
HV	1	0.31				
LV	1	30.41				
'T_{ON}'	1	227.78				
'T_{OFF}'	1	61.2				
Unusual Observations						
Obs	HV	R	Fit	SE	Fit	Residual
9	0.3	1.6	1.37	0.08	0.23	2.14R
R denotes an observation with a large standardized residual.						

The regression model in Table A25 is now re-run omitting the non significant factors i.e. only T_{ON} is considered as a predictor and the following analysis is obtained:

Table A25. Regression model for R of Ti6Al4V with significant predictors.

Regression Analysis: R versus HV						
Weighted analysis using weights in Tm						
The regression equation is						
R = 1.56−0.0059 HV						
Predictor	Coef	SE Coef	T	P	VIF	
Constant	1.55638	0.01991	78.16	0.000		
Analysis of Variance						
Source		DF	SS	MS	F	P
Regression		1	0.0161	0.0161	0.02	0.878
Residual Error		14	9.1967	0.6569		
Total		15	9.2128			

The regression equation in Table A25 shows positive sign prior to T_{ON} which means that higher the T_{ON}, higher the value of R. The value of R-sq (adj) is 19.7% which shows tha the pulse on time predictor accounts for **19.7%** of the total variation calculated from regression equation. It means that, based on the regression analysis, T_{ON} is the significant predictor for R.

Now, the residuals are analyzed for the validation of assumptions of Regression Analysis.

The residual plots for R in Figures A52 and A53 show that residuals are Normally Distributed, show equal variance, are independent of each other and also confirm that one or two points do not overly influence the model.

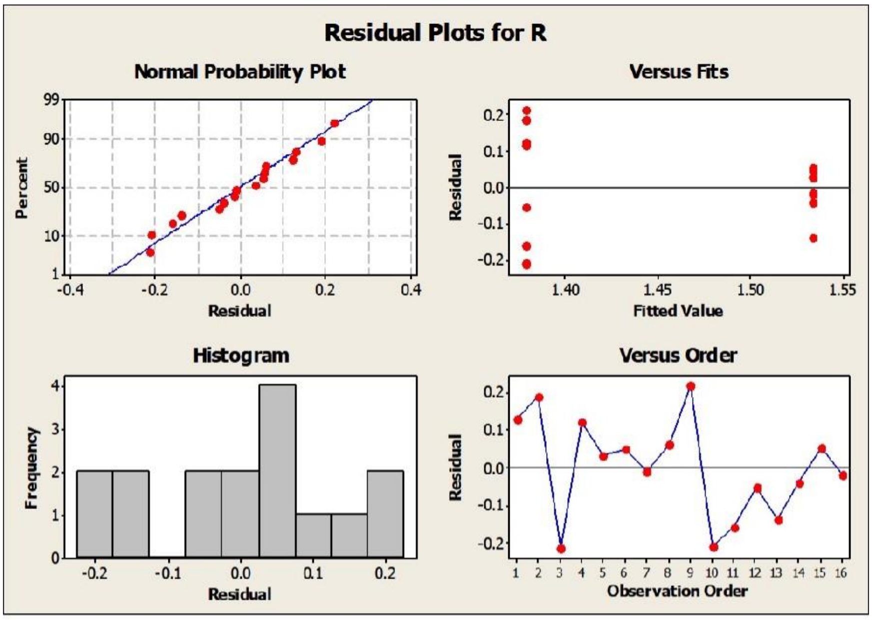

Figure A52. Residual plots for R with T_{ON} as a predictor for Ti6Al4V.

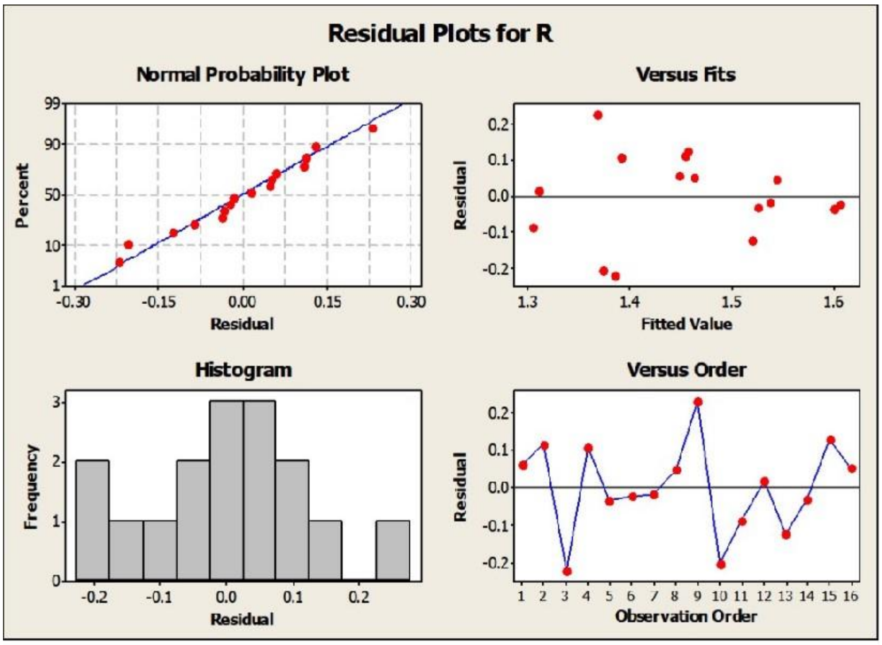

Figure A53. Residual plots for R with all predictors for Ti6Al4V.

Appendix 5

Appendix 5.1. Ti6Al4V workpiece outline

The Ti6Al4V workpiece surface outline images were taken at a magnification level of 22X (Table A26).

Table A26. Ti6Al4VWorkpiece Outline 22X.

Experimental Runs	Replicate # 1	Replicate # 2	Replicate # 3
1			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.3 V, LV = 30 A			
2			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.7 V, LV = 30 A			
3			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.3 V, LV = 50 A			

Continued on next page

Experimental Runs	Replicate # 1	Replicate # 2	Replicate # 3
4			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.7 V, LV = 50 A			
5			
T_{ON} = 6.5 μs, T_{OFF} = 5.5 μs, Duty Factor = 54%, HV = 0.3 V, LV = 30 A			
6			
T_{ON} = 6.5 μs, T_{OFF} = 5.5 μs, Duty Factor = 54%, HV = 0.7 V, LV = 30 A			

Continued on next page

Experimental Runs	Replicate # 1	Replicate # 2	Replicate # 3
7			
T_{ON} = 6.5 µs, T_{OFF} = 5.5 µs, Duty Factor = 54%, HV = 0.3 V, LV = 50 A			
8			
T_{ON} = 6.5 µs, T_{OFF} = 5.5 µs, Duty Factor = 54%, HV = 0.7 V, LV = 50 A			
9			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.3 V, LV = 30 A			
10			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.7 V, LV = 30 A			
11			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.3 V, LV = 50 A			
12			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.7 V, LV = 50 A			
13			
T_{ON} = 6.5 µs, T_{OFF} = 6.5 µs, Duty Factor = 50%, HV = 0.3 V, LV = 30 A			
14			
T_{ON} = 6.5 µs, T_{OFF} = 6.5 µs, Duty Factor = 50%, HV = 0.7 V, LV = 30 A			

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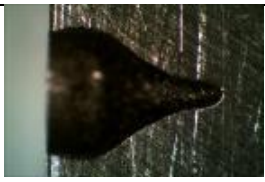
Experimental Runs	Replicate # 1	Replicate # 2	Replicate # 3
15			
T_{ON} = 6.5 μs, T_{OFF} = 6.5 μs, Duty Factor = 50%, HV = 0.3 V, LV = 50 A			
16			
T_{ON} = 6.5 μs, T_{OFF} = 6.5 μs, Duty Factor = 50%, HV = 0.7 V, LV = 50 A			

Appendix 5.2. Copper electrode surface which machined Ti6Al4V

The electrode images that machined Ti6Al4V were taken at a magnification level of 15 X (Table A27).

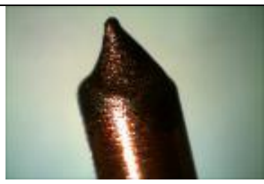
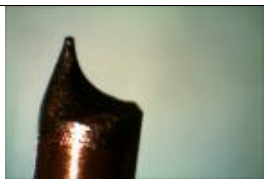
Table A27. Ti6Al4V electrode images Outline 15X.

Experimental Runs	Replicate # 1	Replicate # 2	Replicate # 3
1			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.3 V, LV = 30 A			
2			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.7 V, LV = 30 A			

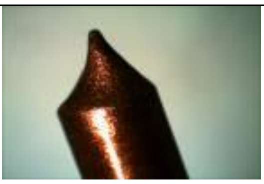
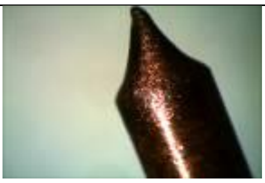
Continued on next page

3			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.3 V, LV = 50 A			
4			
T_{ON} = 4 μs, T_{OFF} = 5.5 μs, Duty Factor = 42%, HV = 0.7 V, LV = 50 A			

Continued on next page

Experimental Runs	Replicate # 1	Replicate # 2	Replicate # 3
5			
T_{ON} = 6.5 µs, T_{OFF} = 5.5 µs, Duty Factor = 54%, HV = 0.3 V, LV = 30 A			
6			
T_{ON} = 6.5 µs, T_{OFF} = 5.5 µs, Duty Factor = 54%, HV = 0.7 V, LV = 30 A			
7			
T_{ON} = 6.5 µs, T_{OFF} = 5.5 µs, Duty Factor = 54%, HV = 0.3 V, LV = 50 A			
8			
T_{ON} = 6.5 µs,T_{OFF} = 5.5 µs, Duty Factor = 54%, HV = 0.7 V, LV = 50 A			
9			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.3 V, LV = 30 A			
10			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.7 V, LV = 30 A			
11			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.3 V, LV = 50 A			
12			
T_{ON} = 4 µs, T_{OFF} = 6.5 µs, Duty Factor = 38%, HV = 0.7 V, LV = 50 A			

Continued on next page

Experimental Runs	Replicate # 1	Replicate # 2	Replicate # 3
13			
T_{ON} = 6.5 µs, T_{OFF} = 6.5 µs, Duty Factor = 50%, HV = 0.3 V, LV = 30 A			
14			
T_{ON} = 6.5 µs, T_{OFF} = 6.5 µs, Duty Factor = 50%, HV = 0.7 V, LV = 30 A			
15			
T_{ON} = 6.5 µs, T_{OFF} = 6.5 µs, Duty Factor = 50%, HV = 0.3 V, LV = 50 A			
16			
T_{ON} = 6.5 µs, T_{OFF} = 6.5 µs, Duty Factor = 50%, HV = 0.7 V, LV = 50 A			