Multiparametric Optimization of Low Plasticity Burnishing Process for AISI 4340 by using Utility Concept

A.P. Kalmegh, P.M. Khodke

Abstract*:. Low plasticity burnishing (LPB®) is an innovative method which provides deep and stable compressive residual stresses. It improves surface characteristic such as low and high cycle fatigue strength, surface finish, microhardness, wear resistance, corrosion resistance, etc. The objective of the multi parametric process optimization for LPB is to find out appropriate levels of process variables i.e. ball diameter, pressure, speed, initial surface roughness and number of passes for achieving optimum values of surface roughness, hardness and fatigue life simultaneously. Considering multiple output responses in the present study, multi response optimization is essential. This paper deals with multi objective LPB process optimization problem of response characteristics with Utility concept for AISI 4340 steel alloy.

LPB® is a registered trademark of Lambda Technologies group.

***Index Terms*: LPB, surface roughness (Ra), surface hardness (Hw), fatigue life (FL), AISI 4340, Utility Concept**

I. INTRODUCTION

For surface enhancements there are many methods. Some of the methods are shot peening, laser peening, water peening, liquid peening, conventional peening, burnishing etc [1]. Out of these methods burnishing is economical tool with simple construction as compared to super finishing, polishing, grinding etc. But as compared to the above methods low plasticity burnishing (LPB®) is an innovative method which produces less cold work with higher depth of compressive residual stresses. The LPB improves surface finish, micro hardness of the surface, corrosion resistance, out of roundness and straightness, wear resistance low and high cycle fatigue strength, foreign object damage (FOD) tolerance, etc. Deep stable layer of compressive residual stress can introduce with LPB, with low cost as compared to the other surface enhancement methods. LPB process can perform on CNC and well as conventional machine tool.

Most of the research work on LPB is done by Paul S. Prevey.Preveyshowed the effect of residual stress and percentage of cold work on depth of compressive layers and residual stresses for material IN718, Ti-6-4 and 17-4 PH steel [2].LPB is also found to improve high cycle fatigue dimension and tolerance of Ti6-Al-4V turbine engine compressor [3]. P.R. Prabhu et.al [4] used LPB for improvement in surface finish for AISI 4140.

Prevey, et.al [5] compared the residual stress and cold work distribution of IN718material produced by LPB with other surface treatment.It has also been studied minimum cold work offers greatest resistance to thermal relaxation at elevated temperature.It is also claimed that 100 times more fatigue life can be obtained for AA 7075-T6 using LPB which is caused due to reduction in corrosion mechanism for AA 7075-T6 [6].

The first LPB model available in literature is developed by Seemikeri [7] with experimental data for enhancement of surface finish, hardness and fatigue life for AISI 1045 considering ball diameter, speed, pressure and number of tool passes as input parameter.Dusaet.al [8] presented mathematical model based on Hook's law and validated using Taguchi orthogonal array considering speed, part diameter and number of passes. Gulhane, et.al [9] also developed experimental model for 316L SS, Ti-6Al-4V, for enhancement of surface finish. Prevey claimed that micro cracks of Ti6-Al-4V can be freely arrested by LPB to the depth of 0.75 mm [10].

An attempt on optimization of LPB by considering all response parameters simultaneously is expected to provide more clarity about usefulness of the process. This paper presents optimization of LPB process with Utility concept to achieve the superior surface finish, increased hardness with high fatigue life for a low cost material AISI 4340 steel alloy.

II. MULTI OBJECTIVE PROCESS OPTIMIZATION

The objective of the multi parametric process optimization for LPB is to find out appropriate levels of process variables i.e. ball diameter, pressure, speed, initial surface roughness and number of passes for achieving optimum values of surface roughness, hardness and fatigue life simultaneously. Considering multiple output responses in the present study, multi response optimization is essential.

This paper deals with multi objective LPB process optimization problem of response characteristics with Utility concept for AISI

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4340 steel alloy on standard specimen [11, 12].

Utility Concept

Utility can be defined as the usefulness of a product or a process with reference to the levels of expectations to the consumers. The utility theory assumes that any decision is made on the basis of the utility maximization principle, according to which, the best choice is the one that provides the highest satisfaction to the decision maker. The weight for each criterion (response) is obtained by intuition and judgment of the decision maker. The performance evaluation of any system depends on number of output characteristics. Therefore, a combined measure is necessary to gauge its overall performance, which must take into account the relative contribution of all quality characteristics. Hence Utility concept requires the priority weight of each response to calculate the overall utility index. Such a composite index represents the overall utility of a product/process. Utility concept has been explored in this work to aggregate multiple responses (objective functions) into an equivalent quality index (single objective function). The overall utility index is then optimized (maximized) finally [13].

The overall usefulness of a process/product can be represented by a unified index termed as Utility which is the sum of the individual utilities of various quality characteristics of the process/product. The methodological basis for Utility approach is to transform the estimated response of each quality characteristic into a common index. If X_i is the measure of effectiveness of an attribute (or quality characteristic) i and there are n attributes evaluating the outcome space, then the Joint Utility Function can be expressed as:

$$U(X_1, X_2, \dots X_n) = f(U_1(X_1), U_2(X_2), \dots \dots \dots U_n(X_n)) \quad (1)$$

Where $U_i(X_i)$ is the utility of the i^{th} attribute

The overall Utility function is the sum of individual utilities if the attributes are independent, and is given as follows:

$$U(X_1, X_2, \dots X_n) = \sum_{i=1}^{n} U_i\ (X_i) \quad (2)$$

The attributes may be assigned weights depending upon the relative importance or priorities of the characteristics. The overall utility function after assigning weights to the attributes can be expressed as:

$$U(X_1, X_2, \dots X_n) = \sum_{i=1}^{n} W_i U_i\ (X_i) \quad (3)$$

Where W_i is the weight assigned to the attribute i, the sum of the weights for all the attributes must be equal to 1.

Determination of Utility Value

A preference scale for each quality characteristic is constructed for determining its utility value. Two arbitrary numerical values (preference number) 0 and 9 are assigned to the just acceptable and the best value of the quality characteristic respectively. The preference number (P_i) can be expressed on a logarithmic scale as follows:

$$Pi = A \times \log\left[\frac{X_i}{X_i^I}\right] \quad (4)$$

Where X_i = value of any quality characteristic or attribute i

X_i^I = just acceptable value of quality characteristic or attribute i

A = constant and can be found by the condition that

At optimum value (X_i*) of attribute i, $P_i = 9$

$$\text{Therefore, } A = \frac{9}{\log\frac{X^*}{X_i}} \quad (5)$$

The overall utility can be expressed as;

$$U = \sum_{i=1}^{n} W_i P_i$$

Subject to condition that $\sum_{i=1}^{n} W_i = 1$

III. EXPERIMENTAL PLAN

Experimentation is carried out on standard fatigue component for AISI 4340 steel alloy [11, 12]. In the present study the objective is to optimize the process for three responses simultaneously. Initially the single factor experimentation is conducted to identify significant factors [11]. The five variables along with their operating ranges have been identified to have significant effect on three output responses. Experimental design methodology, modeling and analysis are carried out to compress the range of input parameters to reach optimal at the earliest [12].

The experiments were carried out with half factorial design with two levels, two replicates and five input factors (25-1). The experimental observations for the plan for each of the 3 response parameters are given in Table 1.

Table 1 Experimental data for 2^{5-1} Plan

Ex. No.	BD (mm)	N (rpm)	P (Kg/cm^2)	NP	Rai (µm)	Ra (µm)	H_w (Hv)	FL*10^5
1	6	180	19	2	5	1.042	463	1.110

2	6	180	19	1	3	0.669	419	1.325
3	6	224	22	2	5	0.458	529	1.180
4	5	224	22	2	3	0.189	524	1.754
5	5	180	19	1	5	1.289	431	1.300
6	5	180	22	2	5	0.813	539	1.390
7	5	224	22	1	5	0.618	449	1.590
8	6	180	22	1	5	1.418	455	1.150
9	5	180	19	2	3	0.389	445	1.483
10	5	180	22	1	3	0.538	452	1.423
11	5	224	19	2	5	0.836	461	1.440
12	5	224	19	2	5	0.751	441	1.640
13	5	224	19	1	3	0.573	421	1.770
14	5	224	22	1	5	0.519	462	1.480
15	6	180	19	2	5	0.989	461	1.190
16	6	224	19	2	3	0.489	431	1.461
17	6	224	22	1	3	0.293	405	1.453
18	6	224	22	2	5	0.438	535	1.350
19	5	180	22	1	3	0.518	461	1.523
20	5	180	19	2	3	0.398	454	1.593
21	5	224	22	2	3	0.109	517	1.730
22	5	180	19	1	5	1.313	451	1.190
23	6	224	19	1	5	1.456	415	1.181
24	6	180	22	1	5	1.396	461	1.143
25	6	224	19	2	3	0.468	441	1.431
26	5	180	22	2	5	0.819	555	1.310
27	6	180	19	1	3	0.658	415	1.309
28	6	180	22	2	3	0.429	510	1.408
29	6	224	19	1	5	1.318	411	1.140
30	6	224	22	1	3	0.271	441	1.399
31	5	224	19	1	3	0.531	425	1.509
32	6	180	22	2	3	0.412	541	1.423

Preference Scale Construction

The preference scale is constructed on the basis of equations 4 and 5. For an example, preference scale is constructed for surface roughness is as follow,

To optimize for Ra, the value is selected as smaller is better. With reference to Table 1;

X*= maximum acceptable value for Ra= 1.456 µm

X1 = optimal value of Ra = 0.109 µm

Using these values and equation (4) and (5), the preference scale (Ra) surface roughness is constructed as,

$$P_{Ra} = 7.994 \times \log\left[\frac{X_{Ra}}{0.109}\right] \quad (6)$$

Another example to construct preference scale for H_w with criteria Higher is better is explained below,

To optimize, the value of H_w is selected as Higher is better,

Hence,

X*= optimal value for H_w= 555 Hv (refer to Table 1)

X1 = minimum acceptable value H_w =405Hv

Using these values and equation (5), the preference scale H_w is constructed as

$$P_{Hw} = 65.771 \times \log\left[\frac{X_{Hw}}{405}\right] \quad (7)$$

Similarly, for all remaining response of FL higher is better condition is applicable

$$P_{FL} = 44.421 \times \log\left[\frac{X_{FL}}{1110318}\right] \quad (8)$$

Table 2 provides calculated value of constant A for all responses.

Table 2 Calculations of Intermediate Constants

Lower is better		Higher is better		Higher is better	
Ra		H_w		Fl	
X*	X1	X*	X1	X*	X1
1.456	0.109	555	405	1770329	1110318
A= 7.994778		A= 65.77122		A=44.42106	

The decision maker has to assign weights. Normally, every parameter is assigned equal weights, here three output parameters are analyzed, and hence weight of 1/3 is equally assigned to each response.

$$W_{Ra} = W_{Hw} = W_{FL} = 1/3 \quad (9)$$

Utility Value Calculation

The utility value of each experiment is calculated using equation (10).

$$U(n,R) = P_{Ra} \times W_{Ra} + P_{Hw} \times W_{Hw} + P_{FL} \times W_{FL} \quad (10)$$

Where, *n* = trial number, 1, 2……..32;

R = replication number,

R= 1, 2

The utility values are calculated using MINITAB analysis software and reported in Table 3

Table 3 Utility Data Based on Response Characteristics (1/3 weightage)

Ra	U Ra	H_w	U H_w	FL	U FL	U overall
1.042	8.16785	463	1770.056	1110318	0	592.7414
0.669	4.21474	419	406.7306	1325395	4527401	1509271
0.458	2.28285	529	4036.008	1180111	1387892	463976.7
0.189	0.3612	524	3855.717	1754553	15487989	5163949
1.289	11.0561	431	766.0103	1300311	3962410	1321062
0.813	5.67226	539	4400.627	1390518	6036567	2013658
0.618	3.72328	449	1322.745	1590331	11023329	3674885
1.418	12.6321	455	1512.945	1150238	783811	261778.9
0.389	1.71838	445	1197.215	1483138	8283690	2761630
0.538	2.98234	452	1417.561	1423029	6812177	2271199
0.836	5.91371	461	1705.406	1440113	7225512	2409074
0.751	5.03284	441	1072.712	1640512	12354356	4118478
0.573	3.30175	421	465.9363	1770329	15932961	5311143
0.519	2.81222	462	1737.7	1480193	8210484	2737408
0.989	7.57314	461	1705.406	1190363	1598585	533432.7
0.489	2.54857	431	766.0103	1461330	7744279	2581683
0.293	1.00598	405	0	1453331	7547997	2515999
0.438	2.11526	535	4254.137	1350332	5098161	1700806

0.518	2.80333	461	1705.406	1523952	9309758	3103822
0.398	1.78974	454	1481.087	1593229	11099375	3700286
0.109	0	517	3605.602	1730249	14807845	4937150
1.313	11.346	451	1385.892	1190193	1595077	532158.2
1.456	13.1044	415	289.1385	1181543	1417218	472506.9
1.396	12.3604	461	1705.406	1143113	641928.2	214548.6
0.468	2.36779	441	1072.712	1431229	7010079	2337051
0.819	5.73503	555	4995	1310003	4179615	1394872
0.658	4.10756	415	289.1385	1309119	4159747	1386680
0.429	2.04087	510	3358.195	1408663	6467663	2157008
1.318	11.4066	411	172.6478	1140339	586919.9	195701.3
0.271	0.857	441	1072.712	1399209	6242485	2081186
0.531	2.91939	425	585.1607	1509563	8945581	2982056
0.412	1.90215	541	4474.189	1423112	6814176	2272884

Determination of Optimal Setting of Parameters

Utility values are analyzed for mean response. Since overall utility is 'higher is better' is selected, the corresponding mean ratios for utility values as single response and the condition "higher is better" are estimated and depicted in Table 4.Considering 'larger the better criteria', values of different variables for combined optimum response, based on mean, are shown. It shows that lower level for BD and Rai and higher level for N, P and NP should be preferred to get optimum performance. The rank indicates the significance level of effect of a variable on response, with 33% weightage.

Table 4 Response Table for Mean of Utility Values with Ranking (1/3 weightage)

LEVEL	BD	N	P	NP	Rai
L-1	**3027052**	1589680	2009550	1910713	**2942062**
L-2	1292819	**2730191**	**2310321**	**2409158**	1377809
Delta	1734233	1140511	300771	498445	1564253
RANK	1	3	5	4	2

IV. Conclusion

It is further observed that the optimum level of input variables, the utility values and also the optimum values of all three response parameters (Ra, Hw and FL) remained unchanged even after the weightages for response function were varied, except when the weightages of any one of the output parameter is considered 100 % neglecting others.

1. For optimization, the maximum utility value is obtained to minimize the surface roughness and to maximize surface hardness and fatigue life.

2. The ranking of the input variables as per Utility value is in the order of Ball Diameter (BD), Initial Surface Roughness (Rai), Speed (N), Number of Passes (NP) and Pressure (P).

3. The multi-parametric optimization with equal weightages (1/3rd) and utility concept yielded the following levels of variables for the test conditions chosen for 25-1 fractional factorial plan.

BD =5 mm,
N=224 rpm,
P=22 Kg/cm2,
NP=2 and
Rai=3 µm

4. The various combinations of weightages for the response functions used in the work have been tried with method of Utility concept and observed that the change in weightage does not result in change in the level of input variables and also the values of different response functions except when the weightage for any one of the output parameter is considered 100 %, neglecting others.

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