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Improvement of Surface Roughness and Hardness using Dimensional Analysis

Manabhanjan Panda[1], Pradeepa Kumar Mohanty[2]
[1, 2] Associate Professor
Department of Mechanical Engineering
Einstein Academy of Technology and Management
Bhubaneswar, Khurdha, Odisha, India

ABSTRACT

From literature survey, proper setting of burnishing parameters is essential to have better surface finish and surface hardness. In this paper, an empirical model of surface roughness (Ra) and hardness (Hw) is proposed for low plasticity burnishing (LPB®) process using dimensional analysis. The proposed method discusses way of selecting the right set of dimensionless group among the different possible combinations and also selecting different respective variable groups. The constants Ra and Hw are evaluated from experimental results. The performance of the developed empirical models is in close agreement with the observed values with correlation coefficient within confidence level.

Keywords: Dimensional Analysis, LPB®, Surface Roughness, Surface Hardness.

1. INTRODUCTION

The recent methods reported in literature for mechanical surface treatments of metals includes conventional burnishing, shot peening, laser peening, water peening, liquid peening, etc [1]. The burnishing is simple in tooling, economical and efficient compared to grinding, honing, super finishing and polishing. These surface enhancement methods have shown their applicability with different degree of freedom. Burnishing process has additional advantages such as increased hardness and fatigue life as a result of compressive residual stresses; wear resistance, etc. [2]. Low Plasticity Burnishing (LPB®) differ from other conventional burnishing processes such as ball burnishing and roller burnishing in a way that it produces less cold work with higher depth of compression. Some of the surface characteristics which can be improved with LPB are surface finish, micro hardness of the surface, low and high cycle fatigue strength, foreign object damage (FOD) tolerance, corrosion resistance, out of roundness and straightness, wear resistance, etc. [3].

LPB produces minimal cold work which offers greatest resistance to thermal relaxation at elevated temperature. Residual stress distribution can exceed well beyond depth of corrosion pitsso as to supress fatigue cracks initiation andcorrosion.

Residual stress and cold work distribution by other surface treatment methods are compared with LPB for1N718 [4]. Fatigue life of AL7075-T6 is at least 100 times greater for LPB caused due to reduction in corrosion mechanism [5]. The investigation for IN718, Ti-6Al-4V, 17-4Ph steel have been carried out to find out the relation between percentage of cold work, depth of compressive layers and residual stresses [6]. LPB (for Ti-6Al-4V) is used to improve high cycle fatigue damage tolerance of turbine engine compressor components [7]. The experimental models for surface finish, hardness and fatigue life are developed using factorial design of experiment, considering ball diameter, speed pressure and no of tool passes as a significant factor for AISI 1045 material [3]. Mathematical model is presented based on Hooke's law and is validated using Taguchi orthogonal array considering speed, part diameter and no. of passes [8]. The experimentation on depth and magnitude of compression and fatigue and damage tolerance has been carried out for turbine blades. The micro cracksare found to be fully arrested by LPB to the depth of 0.75mm. [9]. All four variables ball diameter, speed, feed, no, of tool passes are found significant for surface roughness and hardness. Surface hardness increases with increase in rolling force & ball diameter, whereas it decreases with increase in no. of passes and initial roughness. SR improves with increase in ball diameter, feed and burnishing force & initial roughness [10]. Correlation of surface roughness depends on the work material, as order of significant factors is different for 316 LSS, Ti-6Al-4V. Experimentation with factorial design and ANNOVA gives relation for surface roughness [11].

For traditional roller and ball burnishing much of the knowledge is available as these methods are studied by the many investigators for different applications. However, a little knowledge is available for LPB process to get its maximum efficiency particularly for steel material. Literature review reveals that more study is required to emphasize the benefits of LPB on steel material, particularly for the steel material which has to sustain high load, high temperature, high corrosion environment, etc. there are some materials which can inherently sustain the above requirement due to their desired material composition. But the cost of these materials may be very high. It is required to introduce all the above properties to get benefits of high cost material with low cost material also. LPB proved its utility to enhance the above surface properties with low cost.

This suggest that semi-empirical model developed form observed data incorporating wide range of input output conditions is a better alternative to understand the process more comprehensively. Since properly recorded data fully incorporates the missing knowledge relevant to the major variables, if physical mechanism of the process is unknown, a systematic quantitative analysis of data should lead us to this missing knowledge. The data gathered through extensive and exhaustive experimentations should lead to establishing generalized comprehensive model of LPB system that explains the behavior in a very large majority of situations.

2. DIMENSIONAL ANALYSIS

Dimensional analysis offers a method for reducing complex physical problems to the simplest form prior to obtaining a quantitative answer. The principal use of dimensional analysis is to deduce from a study of the dimensions of the variables in any physical system certain limitations on the form of any possible relationship between those variables [12]. The method is of great generality and mathematical simplicity. At the heart of dimensional analysis is the concept of similarity. In physical terms, similarity refers to some equivalence between two things or phenomena that are actually different. Mathematically, similarity refers to a transformation of variables that leads to a reduction in the number of independent variables that specify the problem [13].

2.1. The steps of dimensional analysis

The premise of dimensional analysis is that the form of any physically significant equation must be such that the relationship between the actual physical quantities remains valid in dependent the magnitudes of the base units [14].

Step1: The independent variables

The first and most important step in dimensional analysis is to identify a complete set of independent quantities *Q1...Qn* that determine the value of *Q0* [12],

Q0= f (Q1, Q2..., Qn)

Step2: Dimensional considerations

Next we list the dimensions of the dependent variable *Q0* and the independent variables *Q1.....Qn*. we must specify at least the type the system of units before we do this. For example, if we are dealing with a purely mechanical problem, all quantities have dimensions of the form $[Q_i] = L^{li}M^{mi}t^{\tau i}$

Where the exponents *li*, *mi* and *τi* are dimensionless numbers that follow from each quantity's definition.

Step3: formation of dimensionless π terms

If there are n numbers of variables and m fundamental dimensions are included then n-m is the number of dimensionless π terms [15]. In order to form these π terms, there is need to choose repeating variables. These variables should be such that:-

a) None of them should be dimensionless,

b) No two variables have the same dimensions,

c) They themselves do not form a dimensionless parameter, and

d) All the fundamental dimensions are included collectively in them.

e) As far as possible, dependent variable should not be a repeating variable.

Moreover, as far as possible, the dependent variable should not be taken as a repeating variable as otherwise it will not be possible to obtain an explicit relationship. ***Π*** term is a combination of 'm' repeating variables with one non repeating variable. The relationship between the dependent variable then can be given as:

$\pi_1 = f(\pi_2, \pi_3, \ldots\ldots \pi_{n-m})$.

3. VARIABLE SELECTION

Preliminary experimentation and technical literature indicated that the increase in hardness in LPB process depends on ball diameter, pressure, speed, initial surface roughness. Whereas as feed, hardness of ball and viscosity of lubricant are not significant. The independent factors considerate to be of principle importance, identified by trial investigation are shown intable1.

In this case, for surface hardness using LPB, following parameters can be considered for analysis.

Table1 Variables, Types, Symbol, with their units and dimensions

Sr. no.	Variables	Type of variable	Symbol	Unit	Dimension
1	Surface roughness	Dependent	R_a	µm	L^1
2	Ball diameter	Independent	D	Mm	L^1
3	Pressure	Independent	P	N/mm^2	$M^1L^{-1}T^{-2}$
4	Speed	Independent	S	Rpm	T^{-1}
5	Initial surface roughness	Independent	R_{ai}	µm	L^1

3.1. Selection of Repeating Variables

There are total 5 variables included therefore n=5M,L and Tare the fundamental dimensions. Hence m=3. So there will be m=3 repeating variables and n-m=2π terms.

Applying the set of rules (section 2.1, steps 3) to choose repeating variables, pressure, speed and ball diameter can be considered best suit for the consideration. So the 2 dimensionless π terms formed by the combination of three repeating and one non repeating variable are listed in table 2.

Table2 list of π terms and repeating and non repeating variables involved in them.

Sr. No.	π term	Repeating variables	Non repeating variable.
π_1	$P^{a1}S^{b1}D^{c1}R_a$	P,S,D	R_a
π_2	$P^{a2}S^{b2}D^{c2}R_{ai}$		Rai

3.2. Construction of dimensionless group

The constants a1, b1, c1, from term π_1, a2, b2, c2, from π_2, can be found out by equating the powers of individual dimensions to zero. For example,

$\pi_1 = P^{a1}S^{b1}D^{c1}R_a$ (1)

Expressing π_1 in dimensions,

$\pi_1 = [M^1L^{-1}T^{-2}]^{a1}[T^{-1}]^{b1}[L]^{c1}[L^1]$

$\pi_1 = M^{(a1)}L^{(-a1+c1+1)}T^{(-2a1-b1)}$

π_1 is dimensionless term, so dimensions for π_1 are M^0 L^0 T^0.

$M^0L^0T^0 = M^{(a1)}L^{(-a1+c1+1)}T^{(-2a1-b1)}$

Equating the powers of π_1 and variables of π_1,

a1=0 (2)

-a1+c1+1=0 (3)

-2a1-b1=0 (4)

Solving the above equations (2), (3), (4) simultaneously, we get,

a1=0

b1=0

c1=-1

Substituting the values in equation (1),

$\pi_1 = P^{-1}S^0D^0R_a$

$\pi_1 = (R_a)/D$ (5)

Similarly, other π terms can be found out. The all 2 π-terms with their description are listed in the table 3.

Table3 Description of Dimensionless group

Sr. No.	Π term	Term name	Physical meaning
π_1	R_a/D	Surface finish number	This will represent the amount of asperities smoothened to decrease the roughness and Improve surface finish.
π_2	Rai/D	Initial surface roughness number	Relative measure of initial surface roughness on final surface roughness.

Application of dimensional analysis to the variables in table 1 with the combination of repeating variables as discussed above leads to the surface roughness equation representing the relationship between variables in terms of dimensionless ratios as,

$$\frac{Ra}{D} = \left(\frac{Rai}{D}\right) \qquad (6)$$

$(\pi 1)(\pi 2)$

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Groups denoted by $\pi 2$ are independent while $\pi 1$ is dependent group. The dimensionless groups given in above equation have physical meaning as given in table 3, and therefore are suitable for experimental planning.

3.3. Test envelope

The test envelope for each of the above dimensionless group has been determined by conducting separate single factor experiments for AISI4340 material and the test points have been decided on the basis of zone of significance of the variable. The chosen values of the variables for experiments and corresponding confidence level and accuracy of measurement are depicted in the table 4.

Table4 Test envelope and test points

Dimensionless Ratio	Independent variable	Test envelope	Test points and their sequence	Measurement of Accuracy
$\pi 2$=(Rai) /D	Rai	3to 7(μm)	3,6,4,7,5	0.001

4. EXPERIMENTATION

In LPB system, the ball is pressurized against rotating work piece. The oil/tool coolant is used to pressurize the bearing, with continuous flow of fluid to support the ball. The ball does not contact the mechanical bearing seat, even under load. The ball is loaded at a normal force to the surface of a component, with a hydraulic cylinder that is in the body of tool. A set up of

Figure1 Experimental setup

newly developed LPB tool is shown in Fig.1.

Table5 Effect of π_2 on π_1

Initial SR(Rai) µm	3	4	5	6	7
Final SR(Ra) µm	0.445	0.754	0.976	1.326	1.886

5. DETERMINATION OF EQUATION CONSTANT:

For evaluating the exponents of the different dimensionless group reflected in equation (6), polynomial relationship $Y = C_n*X^m$ was assumed [13]. Here, C_n is the proportionality constant and m is the exponent associated with the variable X. Then after log conversion,

$$\log Y=\log C_n+m*\log X$$

The value of C_n and m for every dimensional group were obtained using the method of least squares by taking the observed data tabulate in table 5. The values of exponents thus obtained for these groups are presented in table 6.

Table 6 Values of exponents for dimensionless group.

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Group	π_2
Exponent	0.899

On substitution of these exponents in equation (6) and subsequent transformation, the model for surface roughness can be written as,

$$Ra=A(D^{0.101}Rai^{0.899}) \qquad (7)$$

The constant A was evaluated by substituting values of variables and was found equal to 0.3806.

The characteristic variation of surface roughness, obtained from the model is graphically shown in Fig 2.

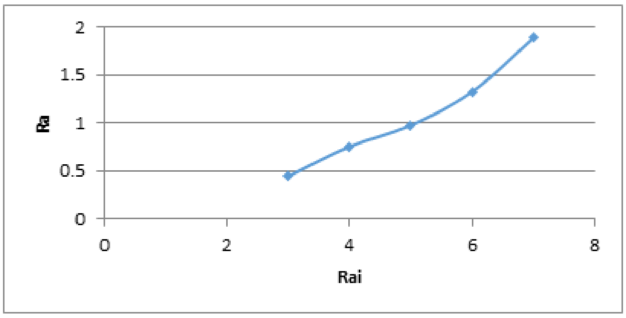

Figure2 Characteristic effect of initial surface roughness on final surface roughness

The observed and predicted values of surface roughness are shown in Fig.3 and it has been found that the correlation between them is 0.9424

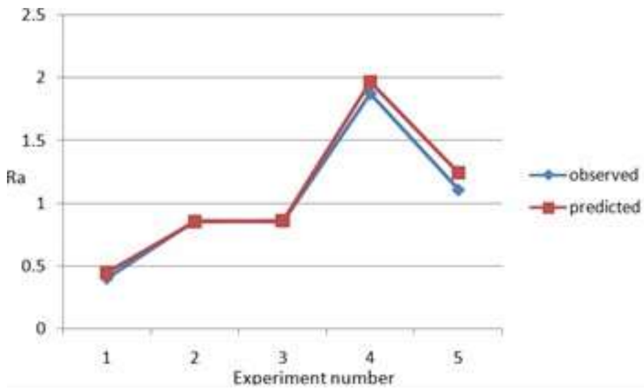

Figure3 Observed and predicted values of surface roughness

Similarly, an empirical model is developed for surface hardness, is as follows:

$$H_w= B\ (P(BD)^{-0.67}Rai^{0.67}) \qquad (8)$$

The constant B was evaluated by substituting values of variables and was found equal to 1511.714.

The observed and predicted values of Surface hardness are shown in fig.4 and it has been found that the correlation between them is 0.9767.

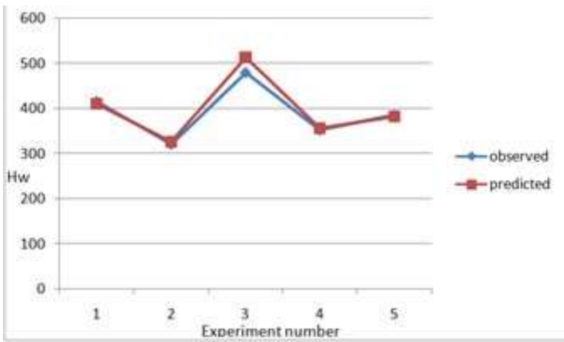

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Figure4observedandpredictedvaluesofsurfacehardness

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6. CONCLUSION

- The semi empirical model represented by equation (7) is complete description of surface roughness. It gives clear idea how ball diameter, initial surface roughness affect on response surface roughness.
- Ball diameter and initial surface have positive effect on surface roughness.
- The semi empirical model represented by equation (8) shows how ball diameter, initial surface roughness and pressure affect on surface hardness.
- Surface hardness increases with increase in pressure, initial surface roughness and decrease in ball diameter.
- The correlations between the observed and predicted value of surface roughness and surface hardness have been found to be 0.9424 and 0.9767 respectively.

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