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Formulation and Comparison of Experimental based Mathematical Model with Artificial Neural Network Simulation on Surface Roughness with Burnished Spherical Surface Tool on Aluminum Alloy6351

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Abstract: This paper deals with the effect of burnishing process on the Aluminum Alloy material 6351(HE 15) using Lathe. Surface roughness generated after the turning operation was used to ball burnishing. The surface roughness pattern which was further used to simulate ball burnishing process using ANN. Improvement in the surface roughness values achieved for tool steel after ball burnishing process was 98.2429%.

Keywords: Burnishing, Surface Roughness, dimensional analysis, Buckingham's π theorem, regression analysis, Mini-max principle, Sensitivity Analysis.

1. Introduction

Inherent irregularities and surface defects like tool marks and surface roughness are developed on the work piece surface after conventional machining processes like turning and milling. These irregularities causes friction and surface damage which leads to low product life, poor metallurgical properties and overall poor product quality. These processes essentially depend on chip removal to attain the desired surface finish and also, skill and the experience of the operator in handling the process. To resolve these problems, burnishing process is applied for better surface finish on the post machined components due to its chip-less and relatively simple operations. A ball burnishing tool consists one or more over-sized balls that are pushed through a hole.

Burnishing is a cold working surface finishing process which is carried out on material surfaces to induce compressive residual stresses and enhance surface qualities. The improvements in surface qualities include reduction in surface roughness, increase in surface hardness, improvement in grain size, wear-resistance, fatigue resistance and corrosion resistance. A burnishing tool typically consists of a hardened sphere which is pressed onto/across the part being processed which results in plastic deformation of asperities into valleys.

Mohammadpour et al. (2010) developed a two-dimensional finite element model for orthogonal cutting of AISI 1045 mild steel, and a numerical solution using the FEM. It investigated the effect of cutting speed and feed rate on residual stresses induced after orthogonal cutting. The stress distribution was found to be increasing with respect to cutting speed and feed rate when the experimental and simulation results were compared.

El-Tayeb et al. (2007) investigated the burnishing process on aluminum 6061 with interchangeable adapter for both roller and ball burnishing process. The effect of different burnishing parameters like burnishing speed, burnishing force and burnishing tool dimension on the surface qualities and properties were investigated. Hamadache et al. (2006) studied the plastic deformation of structural RB40 steel when ball and roller burnishing were performed. It also investigated the roughness, hardness and wear resistance on RB40 steel.

Bouzid et al. (2005) investigated the change in surface roughness of AISI 1042 mild steel after burnishing. A finite element model was formed in which the elastic-plastic behavior of the piece was taken into account to determine the material displacement. The experimental and simulation values were compared and found to be in good correlation.

Yung-Chang Yen (2004) studied the change in residual stress values after hard-turning and after roller burnishing process. The corresponding experimental results were compared with the developed FEM models for roller burnishing process from DEFORM 2D and 3D software. The experimental and simulated values were validated.

Hassan et al. (1996) investigates the change of surface properties for ball-burnishing brass components. A mathematical model called 'surface response methodology' was established to correlate burnishing force and number of

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tool passes, with the surface finish. The model helps in decreasing the number of experiments to be done and it predicts the optimum surface properties.

The above literature review shows the immense scope of development required in the surface characteristics developed by the ball burnishing process. The reason behind this is because of the non-linear characteristic generated on the surface of the workpiece after burnishing process. By carefully modeling the ball burnishing process the prediction of surface characteristic is possible which can be an answer for the time consuming and experimental dependent optimization techniques.
Hence, it was decided to design and fabricate the machine[11-15], which would upgrade the disadvantages offered by the present processing machines[2],[4][8]. The machine was fabricated and tested (shown in figure 1) for all successful test runs and found with good results.

Nomenclatures

R_a	Surface Roughness in µm
E, Es, Ee	Readings of energy meter at start, end and the difference of Ee and Es in Kw-hr
t	Processing time in seconds
H_B	Ball Material used in process (Hardness) in N/mm^2
H_w	Workpiece Material used in process (Hardness) in N/mm^2
A_w	Circumferential Area of Material in mm^2
ω_B	Burnishing Speed for process in rpm
f	Cutting Feed in mm/min
F_B	Burnishing Force in N
D_B	Ball Diameter in mm
D_w	Workpiece Diameter in mm
µ	Cutting Fluid in N-s/mm^2
g	Acceleration due to gravity in m/s^{-2}

Table 1: Specification and Composition of Aluminum Alloy HE15

Alloy(ISS)	OLD	HE15
INDIAN	NEW	24345
Equivalent Alloy(AA)USA	AA	2014
Copper	Min	3.8
	Max	5.0
Magnesium	Min	0.2
	Max	0.8
Silicon	Min	0.5
	Max	1.2
Iron	Max	0.7
Manganese	Min	0.3
	Max	1.2
Others (Total)	Max	0.5

2. Experimental Procedures:

Ball Burnishing tool shown in figure 1 is utilized for burnishing operation in this paper. In figure 2 is showing the measurement of surface roughness on the material used. The process of formulation of mathematical model for aluminum alloy operation and its analysis is mentioned this paper.

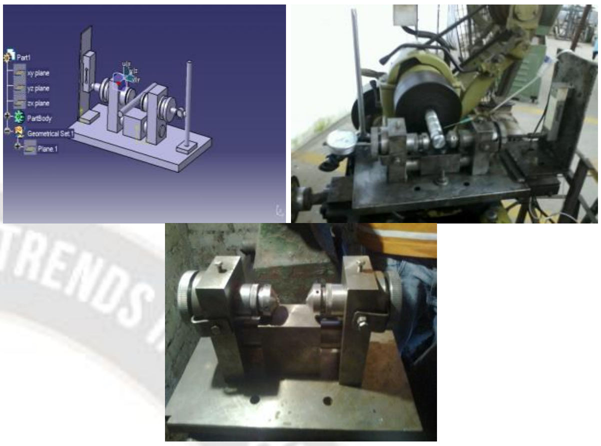

Figure 1: Fabricated Burnishing Tool using Lathe Machine

Figure 2: Processing Aluminum Alloy and Measurement operation

For experimentation purpose workpiece samples of same sizes were collected. In processing, the objective of the experiment is used to gather information through experimentation for formulation of mathematical model for HE15 material operation. During processing operations for the measurement force is measured using specially designed force tool dynamometer electronic kit. Energy and time is measured using energy meter and stopwatch respectively. Pilot experiments were performed to select test envelope and test points of process parameters for experimental design. These process parameters were used in experimental design for the investigation of process parameters like processing Energy, surface roughness and time during operation. The observed values of processing surface roughness, energy and time are

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recorded for formulation of mathematical model. In operation all twelve selected independent process parameters were manipulated on processing machine and observations were taken out at a speed of 340 rpm, 560 rpm and 800 rpm.

3. Design of Experiments:

In this study, 70 experiments are designed on the basis of sequential classical experimental design technique [21] that has been generally proposed for engineering applications. The basic classical plan [17] consists of holding all but one of the independent variables constant and changing this one variable over its range. The main objective of the experiments consists of studying the relationship between 9 independent process parameters with the Ra, E and t dependent responses for Internal knot removal. Simultaneous changing of all 9 independent parameters was cumbersome and confusing. Hence all 21 independent process parameters were reduced by dimensional analysis. Buckingham's π theorem was adapted to develop dimensionless π terms for reduction of process parameters. This approach helps to better understand how the change in the levels of any one process parameter of a π terms affects E, R_a and t response. A combination of the levels of parameters, which lead to maximum, minimum and optimum response, can also be located through this approach. Regression equation models of burnishing were optimized by mini-max principle.

3.1 Formulation of Approximate Generalized Experimental Data Base Model by Dimensional Analysis:

As per dimensional analysis [23], Processing Energy (E) was written in the function form as:

$E=f\,(H_B, H_w, A_W, \boldsymbol{\omega_B}, f, F_B, D_B, N, \mu, \mathbf{g})$

By selecting Mass (M), Length (L) and Time (θ) as the basic dimensions, the basic dimensions of the forgoing quantities were mentioned. According to the Buckingham's - theorem, (n- m) number of dimensionless groups [21] are forms. In this case n is 9 and m=3, so π_1 to π_{11}dimensionless groups were formed. By choosing 'F_B ', 'g' and 'ω_B' as a repeating variable, eleven π terms were developed as follows:

$$\left(\frac{E\,.\,\omega_B^2}{F_B.\,g}\right) = f\,x\left\{\left(\frac{H_W}{H_B}\right)\left(\frac{A_W\,.\,\omega_B^4}{g^2}\right)\left(\frac{f.\,\omega_B}{g}\right)\left(\frac{D_B.\,\omega_B^2}{g}\right)\left(\frac{\mu.\,g^2}{\omega_B^3.\,F_B}\right)\right\}$$

$$E_{01} = K.\left(\frac{F_B\,.\,g}{\omega_B}\right)\left\{\left(\frac{H_W}{H_B}\right)\left(\frac{A_W\,.\,\omega_B^4}{g^2}\right)\left(\frac{f.\,\omega_B}{g}\right)\left(\frac{D_B.\,\omega_B^2}{g}\right)\left(\frac{\mu.\,g^2}{\omega_B^3.\,F_B}\right)\right\}$$

3.2 Reduction of independent variables/dimensional analysis:

When n (no. of variables) is large, even by applying Buckingham's π theorem number of π terms will not be reduced significantly than number of all independent variables. Thus, much reduction in number of variables is not achieved. It is evident that, if we take the product of the π terms it will also be dimensionless number and hence a π term. This property is used to achieve further reduction of the number of variables. Thus few π terms are formed by logically taking the product of few other π terms and final mathematical equations are given below:

Π_{0Ra1}= Mathematical Equation for Processing Surface Roughness (R_{a1}):

$$\pi_{0Ra1} = 1.84X10^{-4}.\left(\frac{g}{\omega_B^2}\right)\left\{\left(\frac{H_W}{H_B}\right)^{-3.22}\left(\frac{A_{W.\omega_B^4}}{g^2}\right)^{1.24}\left(\frac{f.\,\omega_B}{g}\right)^{-0.0031}\left(\frac{D_B.\,\omega_B^2}{g}\right)^{-1.18}\left(\frac{\mu.\,g^2}{\omega_B^3.\,F_B}\right)^{0.28}\right\} \quad (3)$$

Π_{0E1} = Mathematical Equation for Energy (E_1):

$$\pi_{0E1} = 1.14X10^{14}\left(\frac{F_B.\,g}{\omega_B^2}\right)\left\{\left(\frac{H_W}{H_B}\right)^{13.93}\left(\frac{A_{W.\omega_B^4}}{g^2}\right)^{-5.35}\left(\frac{f.\,\omega_B}{g}\right)^{0.063}\left(\frac{D_B.\,\omega_B^2}{g}\right)^{10.61}\left(\frac{\mu.\,g^2}{\omega_B^3.\,F_B}\right)^{-0.69}\right\} \quad (4)$$

Π_{0t1}= Mathematical Equation for Processing time (t_1):

$$\pi_{0t1} = 1.23X10^{8}K.\,(\omega_{B.t})\left\{\left(\frac{H_W}{H_B}\right)^{8.77}\left(\frac{A_{W.\omega_B^4}}{g^2}\right)^{-2.63}\left(\frac{f.\,\omega_B}{g}\right)^{0.0021}\left(\frac{D_B.\,\omega_B^2}{g}\right)^{5.087}\left(\frac{\mu.\,g^2}{\omega_B^3.\,F_B}\right)^{-0.45}\right\} \quad (5)$$

The relationship between various parameters was unknown. The dependent parameter Π_{0Ra1}, Π_{0E1} and Π_{0t1} i.e. relating to R_a E, and t were bear an intricate relationship with remaining terms (i.e. π_1 to π_5) evaluated on the basis of experimentation. The true relationship is difficult to obtain. The possible relation may be linear, log linear, polynomial with n degrees, linear with products of independent π_i terms. In this manner any complicated relationship can be evaluated and further investigated for error. Hence the relationship for R_a was

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formulated as: $\pi_{01}=k_1 \times (\pi_1)^{a1} \times (\pi_2)^{b1} \times (\pi_3)^{c1} \times (\pi_4)^{d1} \times (\pi_5)^{e1}$ (6)

Equation is modified as: Obtaining log on both sides we get,

$\text{Log}\pi_{01}=\text{log}k1+ a_1\log \pi_1+ b_1\log \pi_2+ c_1\log \pi_3 + d_1\log \pi_4 + e_1\log \pi_5$

This linear relationship now can be viewed as the hyper plane in seven dimensional spaces.

3.2 Model Formulation: It is necessary to correlate quantitatively various independent and dependent terms involved in this very complex phenomenon. This correlation is nothing but a mathematical model as a design tool for such situation. The mathematical model for internal knot removal operation is shown below:

Π_{0Ra1}= Mathematical Equation for Processing Surface Roughness

$R_{amin}=1.85X10^{-04}x(4.847734)[(0.220183)^{-3.2251}x(25.2303)^{1.2472}x(4.27x10^{-5})^{-0.0031}x(10.38207)^{-1.1813}x(2.289x10^{-9})^{0.2813}] = 0.001596613$ mm

Π_{0E1}= Mathematical Equation for Energy (E):

$E_{min}=(1.14X10^{+14})X(9096.54306)[(0.220183)^{13.9306}x(773.3862)^{-5.3542}x(6.05x10^{-6})^{0.0628}x(1.875261)^{10.6063}x(8.9x10^{-8})^{-0.6915}]=7.8702X10^{-11}$ Kw-hr

Π_{0t1}= Mathematical Equation for Processing time (t):

$t_{min}=(123338879.9)X(2.02108771)[(0.220183)^{8.7733}x(773.3862)^{-2.6305}x(6.05x10^{6})^{0.0021}x(1.87526)^{5.0868}x(8.9x10^{-8})^{-0.446}]=0.003747442$ sec

4. Reliability of Model:

(Rs) $= 1 - \prod_{i=1}^{n}(R_i)$ and for the parallel system the reliability of system is calculated by relation: System Reliability (Rp) = $1 - \prod_{i=1}^{n}(1 - R_i)$ Therefore reliability of the system for this case is given by System Reliability

(Rp)= $1 - \prod_{i=1}^{n}(1 - R_i)$ =1-[(1-RRa)*(1-RiE)*(1-Rit)] since, observations were taken simultaneously during experimentation. Reliability of model is established using relation Reliability =100-% mean error and Mean error = where, xi is % error and fi is frequency of occurrence. Therefore total reliability of model for material is equal to 1-[(1-0.882857)(1-0.14286)(1-0.825)=0.982429= 98.2429% .

5. Process Parameters Selection by Mini-Max Principle (Estimation of Limiting Values of Response Variables)

From above mathematical models the obvious aim was to minimize the values of Ra, E, and t. The ultimate objective of this work is not merely developing the models but to find out best set of variables, which will result in maximization/minimization of the response variables. In this section attempt is made to find out the limiting values of three response variables viz. processing Surface Roughness, energy and time. To achieve this, limiting values of independent π term viz. π_1, π_2, π_3, π_4, π_5 are put in the respective models. In the process of minimization, minimum value of independent π term is put in the model if the index of the term was positive and maximum value is put if the index of the term was negative. (7)

6. Optimization

Optimization of internal knot removal operation is to search an optimal solution for a given objectives satisfying the required constraints. The objective was to minimize Processing

Table 2: Limiting Values of Response Variables

Max and Min. of Response π terms	**HE 15 Surface Roughness(Π_{Ra1})**	**Energy (Π_{E1})**	**Time(Π_{t1})**
Maximum	**1.84013E+12**	**8.85315E+16**	**192436353.3**
Minimum	**9.89841E+14**	**1.64582E+14**	**14025618.16**

Torque, Energy and time with the constraints involved were bound values of π terms. This adds to the complexities of the problem. Linear programming is a strong tool to optimize where the objective function and the constraints are linear. Based on the computed results, LPP model was formulated. This can be achieved by taking the log of both the sides of the model.

Taking log of both the sides of the Equation 8, we get

Log (Π_{01}) =log ($1.85X10^{-04}$) + log (4.847734) -3.2251xlog$\left(\frac{H_W}{H_B}\right)$ +1.2472x

Z = K+ K_1+ a x X_1+ b x X_2+ c x X_3+d x X_4+ e x X_5 (8)&

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Z = log(1.85X10^{-04})+ log(4.847734) -3.2251xlog (π_1) +1.2472x log (π_2)-0.0031xlog (π_3)-1.1813 x log (π_4)-0.2813 x log (π_5)

Z (Surface roughness: Π_{0Ra1} min) = 1.85X10^{-04}+4.847734 - 3.2251 x X_1+1.2472xX_2-0.0031xX_3-1.1813xX_4+0.2813xX_5 (9)

Similar procedure is also adopted for Eqn. 10 and 11, we get

Z (Energy: Π_{0E1}min) = 1.14E+14+9096.54306+ 13.9306 x X_1 -5.35420x X_2 -0.0628 x X_3+10.6063 x X_4 -0.6915 x X_5 (10)

Z (Energy: Π_{0E1}min) = 1.14E+14+9096.54306+ 13.9306 x X_1 -5.35420x X_2 -0.0628 x X_3+10.6063 x X_4 -0.6915 x X_5

(11)

7. Topology:

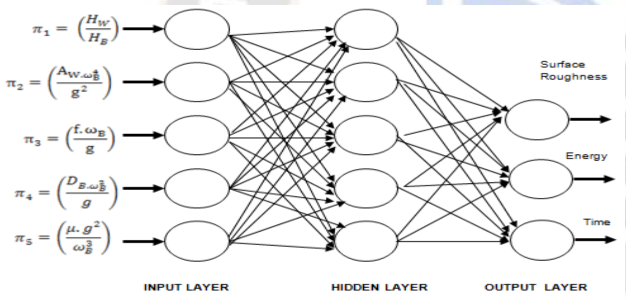


Figure 3: Topology of operation on HE15

8. Sensitivity Analysis

The influence of the various independent π terms has been studied by analyzing the indices of the various π terms in the models. Through the technique of sensitivity analysis, the change in the value of a dependent π term caused due to an introduced change in the value of individual π term is evaluated. In this case, a change of ± 10 % is introduced in the individual independent π term independently (one at a time).Thus, total range of the introduced change is 20 %. The effect of this introduced change on the change in the value of the dependent π term is evaluated. The average values of the change in the dependent π term due to the introduced change of 20 % in each independent π term. This is called as sensitivity. The total % change in output for ±10% change in input are shown in Table 7.8 to Table 7.12 and Table 7.13 shows Nature of variation in response variables due to increase in the values of independent pi terms for all five processing operations. Table 7.14 shows sequence of influence of independent pi terms on dependent pi terms for all five processing operations. Figure 7.6 to figure 7.10 shows graphs of sensitivity analysis of dependent pi terms.

8.1 Effect of introduced change on the dependent pi term π_{0Ra1}

When a total change of ±10% is introduced in the value of independent pi term π_1, a change of about 22.61% occurs in the value of π_{0Ra1} (computed from the model). The change brought in the value of π_{0Ra1} because of change in the values of the other independent pi term π_5 is only 2.39%. Similarly the change of about 22.61%, 51.05%, 51.29% and 112.50% takes places because of change in the values of π_5, π_2, π_1, π_3 and π_4 respectively.

It can be seen that highest change takes place because of the pi term π_4, whereas the least change takes place due to the pi term π_5. Thus, π_4 is the most sensitive pi term and π_5 is the least sensitive pi term. The sequence of the various pi terms in the descending order of sensitivity is π_2, π_1 and π_3.

8.2 Effect of introduced change on the dependent pi term π_{0E1}

When a total change of ±10% is introduced in the value of independent pi term π_1, a change of about 13.93% occurs in the value of π_{0E1} (computed from the model). The change brought in the value of π_{0E1} because of change in the values of the other independent pi term π_3 is only 1.25%. Similarly the change of about 13.94%, 111.76%, 242.09% and 354.20% takes place because of change in the values of π_3, π_5, π_2, π_4 and π_1 respectively.

It can be seen that highest change takes place because of the pi term π_1, whereas the least change takes place due to the pi term π_3. Thus, π_1 is the most sensitive pi term and π_3 is the least sensitive pi term. The sequence of the various pi terms in the descending order of sensitivity is π_5, π_2 and π_4.

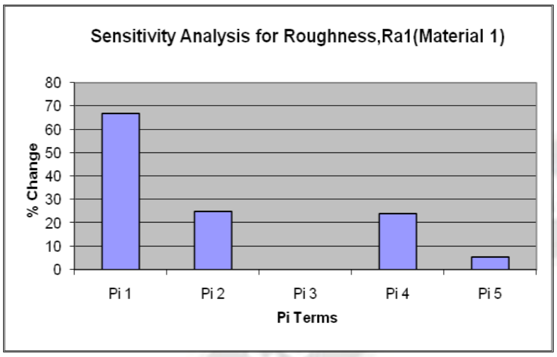
8.3 Effect of introduced change on the dependent pi term π_{0t1}

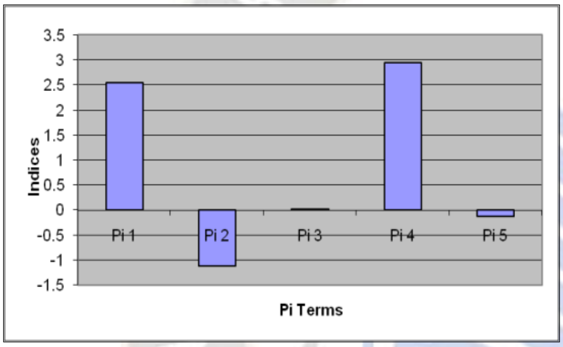
When a total change of ±10% is introduced in the value of independent pi term π_1, a change of about 9.05% occurs in the value of π_{0t1} (computed from the model). The change brought in the value of π_{0t1} because of change in the values of the other independent pi term π_3 is only 0.042%. Similarly the change of about 9.05%, 54.31%, 101.00% and 168.41% take place because of change in the values of π_5, π_2, π_4 and π_1 respectively.

It can be seen that highest change takes place because of the pi term π_1, whereas the least change takes place due to the pi term π_3. Thus, π_1 is the most sensitive pi term and π_3 is the least sensitive pi term. The sequence of the various pi terms in the descending order of sensitivity is of $\pi5$, π_2, π_4 and π_1.

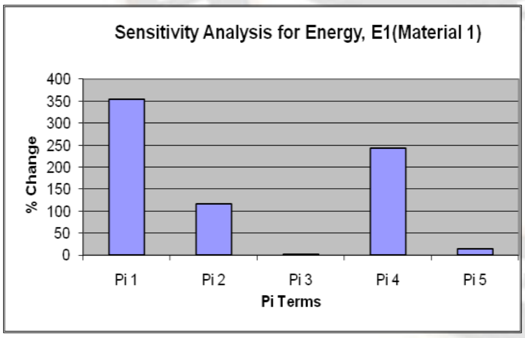
Graph of Sensitivity Analysis and Indices for Operation on Material HE15 follows:

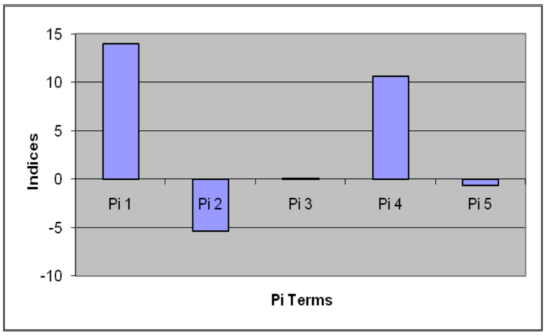
Surface Roughness:



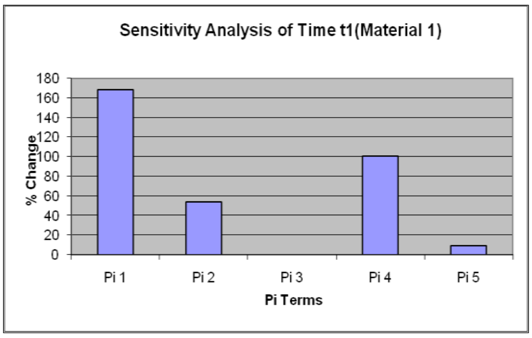


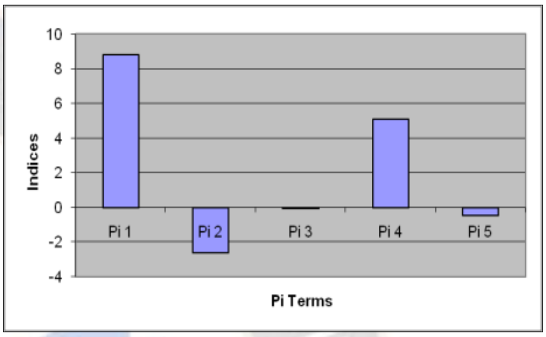
Energy:





Time:





Graph of Sensitivity Analysis and Indices for Operation on Material HE15

9. Conclusions:

1. The dimensionless π terms have provided the idea about combined effect of process parameters in that π terms. A simple change in one process parameter in the group helps the manufacturer to maintain the required E, R_a and t values so that the productivity is increased.

2. The mathematical models developed with dimensional analysis for material HE15 can be effectively utilized for aluminum alloy processing operations.

3. The computed selection of material HE15 process parameters by dimensional analysis

provides effective guidelines to the manufacturing engineers so that they can minimize E, R_a

and t for higher performances.

4. The models have been formulated mathematically. From the values of % errors, it seems that the mathematical models can be successfully used for the computation of dependent terms for a given set of independent terms. Industries can use the data for calculation surface finish and speed estimation for material processing on Lathe.

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