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PREDICTION OF MACHINABILITY OF SINTERED IRON COMPONENT USING RESPONSE SURFACE METHOD

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ABSTRACT

In the present study an attempt has been made to investigate the machinability of Powder Metallurgy components. According to the literature review on this topic it has been found that very little effort has been expended so far on studying the effect of machining parameters and process variables on the machinability of Powder Metallurgy components. So it was felt necessary to carry out a systematic study of the above parameters and processes of Powder Metallurgy components. These investigations were based on Design of Experiments Technique in order to achieve optimum machinability of such components. Compacting pressure, sintering temperature and sintering time are considered as the controllable process parameters and cutting forces as the response variable. A second order response surface model (RSM) has been used to develop a predicting equation of cutting force based on the data collected by a statistical design of experiments known as central composite design (CCD). The analysis of variance (ANOVA) shows that the observed data fits well into the assumed second order responses surface model.

Keywords: Sintered components, response surface, central composite design.

INTRODUCTION

The Powder Metallurgy process has created an immense interest in many parts of the world as an economic method of producing components from metal powders (Ferguson, 1983; German, 1994). Normally it eliminates the need of secondary operations like turning, milling etc. However, to produce certain geometrical features like transverse holes, undercuts etc, some machining operations like turning and drilling are indispensable. As the use P/M materials are increasing day by day and to increase the productivity, the study of their machinability has become important (Salak *et al*., 2005). There is ample evidence from test on a wide variety of materials that machinability depends on work piece, tool material properties, cutting parameters, rigidity of the machine tools (Bothyord, 1987). It has been reported that cutting characteristics of work piece material are controlled by the alterations of the microstructure through changes in chemical compositions, additional free machining additives or by a variety of mechanical treatments (Anderson and Hirschhorn, 1977; Smith, 1990; Agapiou and Devries, 1988). Very little investigation has been carried out on the machinability of sintered P/M components (Engstrom, 1983; Salak *et al*., 2006). Moreover, machinability could not be predicted solely from the knowledge of the work piece and cutting tool properties but it is commonly determined through machining tests Measurement of cutting forces during machining processes is very important parameter and basic step to determine the machinability and performance of the workpiece. Therefore it is being felt necessary to study the effect of different process parameters on the machinability of iron P/M components. The difference of machining behavior of the P/M components with wrought products may be a subject of interest to the researchers as well as to the practicing engineers. In the present study, P/M preforms produced at different process parameters and examined the changes of Tangential cutting force during machining of the preforms at different cutting speeds. A 2^3 full factorial design of experiments (DOE) have been used to perform statistical analysis about the influence of various process parameters on the machinability of iron P/M components and a second order response surface method (RSM) have been used to developed the predicting equations of cutting forces at different cutting speed of the developed component with the variation of process parameters (Chatterjee *et al*., 2007; Boxes *et al*., 1987; Montgomery, 1991).

Experimental procedures

The iron powder used for the present investigation has been provided by Kawasaki Steel Corporation Chiba Works, Chiba, Japan. The chemical analysis and powder particle size distribution was provided by the said company as given in table 1.

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Table 1. Chemical Analysis of iron powder (weight %).

C	Si	Mn	P	S	O	Total. Fe
0.001	0.02	0.17	0.013	0.010	0.129	Balance

Powder Properties:

Apparent Density (gm/cc): 2.94
Flow (50gm/s) : 24.7

Sieve Distribution:

Sieve Number	Size	Cumulative wt%
+ 100#	> 150 um	8.5
+ 150#	> 106 um	20.1
+ 200#	> 75 um	22.9
+ 250#	> 63 um	9.5
+ 325#	> 45 um	16.8
- 325#	< 45 um	22.2

The iron powder was compacted in a closed cylindrical die using 120 Ton hydraulic press (Lawrence & Mayo) for manufacturing of green samples (Fig. 10). Before compaction, the die and punch were lubricated with *Zn*-stearate. The sintering process was carried out in vacuum furnace (1450°C) using argon as an inert ambient (Fig. 11). The objective of present study is to throw light on the machinability of the compacted sintered samples under different processing conditions. In this context 60 different P/M components (25mm diameter) were produced as per the design of experiment (DOE). Related machining parameter like cutting forces during machining of these samples were studied against the variation of controllable input process variables like compaction pressure, sintering time and sintering temperature. In this experiment three different cutting speeds were used to find out the tangential cutting forces under constant depth of cut (0.50mm) and feed (0.1 mm/rev). The use of low feed minimizes the effect of temperature influence on the work piece. Cutting forces were measured in the lathe tool dynamometer (Strain gauge type, Syscon Instruments Pvt. Ltd., Bangalore, India) and relevant cutting tool (tungsten carbide) used was TCMX 11 03 04 - WF12 grade supplied by Sandvik India Ltd. The results obtained through the experiments are given in table 2 and all the available data have been analyzed using response surface method and using Minitab software (Version 14).

Effect of process parameters on machinability is illustrated below.

In order to perform test of significance for individual process parameters as well as their interactions, the following standard equation is considered.

$$R2 = \beta_o + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + \varepsilon, \quad (1)$$

The corresponding fitted equation can be expressed as follows:

$$\acute{R}2 = E\,(R2 - \varepsilon)$$
$$= \hat{\beta}_o + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_{12} x_1 x_2 + \hat{\beta}_{13} x_1 x_3 + \hat{\beta}_{23} x_2 x_3 + \hat{\beta}_{123} x_1 x_2 x_3. \quad (2)$$

Table 2 shows the parameter settings for performing statistical test on the degree of significance of process parameters and their interactions. For any factor z_i, the transformation from actual to coded values has been performed considering the equations (3) – (5) as given below:

$$z_i^o = \frac{z_i^{max} + z_i^{min}}{2}, \quad (3)$$

$$\Delta z_i = \frac{z_i^{max} - z_i^{min}}{2}, \quad (4)$$

$$x_i = \frac{z_i - z_i^o}{\Delta z_i}. \quad (5)$$

A full factorial experimental design (l^k) with six additional central points (n_c) has been considered for performing the statistical analysis. The six additional central points give an estimate of experimental error. Table 2 gives the observed data for different settings of process parameters. The data have been collected conducting the experiments in a random order of run numbers and equation (1) has been developed using observed data obtain from the experiment using MINITAB software (Version 14). The coefficients of the fitted equations can be obtained from equation (6) as given below [16].

$$\mathbf{B_1} = (\mathbf{X}^T \mathbf{X})^{-1} \mathbf{X}^T \mathbf{T_f}, \quad (6)$$

where

$$\mathbf{B_1} = [\hat{\beta}_0 \;\; \hat{\beta}_1 \;\; \hat{\beta}_2 \;\; \hat{\beta}_3 \;\; \hat{\beta}_{12} \;\; \hat{\beta}_{13} \;\; \hat{\beta}_{23} \;\; \hat{\beta}_{123}]^T,$$
$$\mathbf{X} = [\mathbf{x_0} \;\; \mathbf{x_1} \;\; \mathbf{x_2} \;\; \mathbf{x_3} \;\; \mathbf{x_{12}} \;\; \mathbf{x_{13}} \;\; \mathbf{x_{23}} \;\; \mathbf{x_{123}}],$$
$$\mathbf{x_o} = [1 \;\; 1 \;\; 1 \;\; 1 \;\; 1 \;\; 1 \;\; 1 \;\; 1]^T,$$
$$\mathbf{x_1} = [-1 \;\; 1 \;\; -1 \;\; 1 \;\; -1 \;\; 1 \;\; -1 \;\; 1]^T,$$
$$\mathbf{x_2} = [-1 \;\; -1 \;\; 1 \;\; 1 \;\; -1 \;\; -1 \;\; 1 \;\; 1]^T,$$
$$\mathbf{x_3} = [-1 \;\; -1 \;\; -1 \;\; -1 \;\; 1 \;\; 1 \;\; 1 \;\; 1]^T$$
$$\mathbf{x_{12}} = [1 \;\; -1 \;\; -1 \;\; 1 \;\; 1 \;\; -1 \;\; -1 \;\; 1]^T,$$
$$\mathbf{x_{13}} = [1 \;\; -1 \;\; 1 \;\; -1 \;\; -1 \;\; 1 \;\; -1 \;\; 1]^T,$$
$$\mathbf{x_{23}} = [1 \;\; 1 \;\; -1 \;\; -1 \;\; -1 \;\; -1 \;\; 1 \;\; 1]^T,$$
$$\mathbf{x_{123}} = [-1 \;\; 1 \;\; 1 \;\; -1 \;\; 1 \;\; -1 \;\; -1 \;\; 1]^T,$$

In order to get the regression equations of Tangential cutting force (R_2) using the data of table 2, we have used the Minitab statistical software to get the desire result more precisely.

The following ANOVA observations were done at 3 different cutting speeds.

Table 2. Observed Tangential cutting forces at different cutting speed – values for different settings of process parameters based on 2^3 full factorial designs.

Sl. No.	Coded Value of Parameters			Actual Value of Parameters			Response variables Tangential Cutting Forces. (Kgf.)		
	x_1	x_2	x_3	Compaction Ton	Sintering. Temp °c	Sintering. Time hour	R2 (@ cutting speed 4.24 m/min.)	R2 (@ cutting speed 18.37m/min)	R2 (@ cutting speed 27.95 m/min)
1	-1	-1	-1	17.66	975	1	14	16	15
2	1	-1	-1	26.49	975	1	18	21	18
3	-1	1	-1	17.66	1125	1	12	15	16
4	1	1	-1	26.49	1125	1	19	20	18
5	-1	-1	1	17.66	975	2	17	18	16
6	1	-1	1	26.49	975	2	19	20	18
7	-1	1	1	17.66	1125	2	13	15	14
8	1	1	1	26.49	1125	2	22	21	18
9	-1.6818	0	0	14.6499	1050	1.5	11	15	11
10	1.68179	0	0	29.5001	1050	1.5	27	23	20
11	0	-1.6818	0	22.075	923.87	1.5	16	17	16
12	0	1.68179	0	22.075	1176.13	1.5	19	18	17
13	0	0	-1.6818	22.075	1050	0.6591	16	16	16
14	0	0	1.68179	22.075	1050	2.3409	16	18	17
15	0	0	0	22.075	1050	1.5	18	16	14
16	0	0	0	22.075	1050	1.5	17	16	15
17	0	0	0	22.075	1050	1.5	19	18	16
18	0	0	0	22.075	1050	1.5	18	18	16
19	0	0	0	22.075	1050	1.5	17	17	16
20	0	0	0	22.075	1050	1.5	15	18	15
21	-1	-1	-1	17.66	975	1	13	15	14
22	1	-1	-1	26.49	975	1	18	20	17
23	-1	1	-1	17.66	1125	1	14	16	16
24	1	1	-1	26.49	1125	1	18	21	18
25	-1	-1	1	17.66	975	2	16	17	15
26	1	-1	1	26.49	975	2	19	21	19
27	-1	1	1	17.66	1125	2	14	16	15
28	1	1	1	26.49	1125	2	21	20	19
29	-1.6818	0	0	14.6499	1050	1.5	10	15	10
30	1.68179	0	0	29.5001	1050	1.5	26	24	19
31	0	-1.6818	0	22.075	923.87	1.5	17	18	17
32	0	1.68179	0	22.075	1176.13	1.5	18	19	17
33	0	0	-1.6818	22.075	1050	0.6591	17	16	16
34	0	0	1.68179	22.075	1050	2.3409	16	17	17
35	0	0	0	22.075	1050	1.5	17	17	16
36	0	0	0	22.075	1050	1.5	17	18	16
37	0	0	0	22.075	1050	1.5	18	17	17
38	0	0	0	22.075	1050	1.5	19	18	17
39	0	0	0	22.075	1050	1.5	18	18	16
40	0	0	0	22.075	1050	1.5	16	17	16
41	-1	-1	-1	17.66	975	1	14	16	16
42	1	-1	-1	26.49	975	1	19	20	19
43	-1	1	-1	17.66	1125	1	14	17	15
44	1	1	-1	26.49	1125	1	19	21	18
45	-1	-1	1	17.66	975	2	16	18	16
46	1	-1	1	26.49	975	2	20	21	17
47	-1	1	1	17.66	1125	2	15	16	13
48	1	1	1	26.49	1125	2	21	21	19
49	-1.6818	0	0	14.6499	1050	1.5	12	14	11
50	1.68179	0	0	29.5001	1050	1.5	28	23	21
51	0	-1.6818	0	22.075	923.87	1.5	17	17	17
52	0	1.68179	0	22.075	1176.13	1.5	20	18	18
53	0	0	-1.6818	22.075	1050	0.6591	16	17	16
54	0	0	1.68179	22.075	1050	2.3409	18	19	17
55	0	0	0	22.075	1050	1.5	17	17	15
56	0	0	0	22.075	1050	1.5	18	18	16
57	0	0	0	22.075	1050	1.5	20	19	16
58	0	0	0	22.075	1050	1.5	17	18	17

Table 3. Analysis of variance (ANOVA).

For cutting speed 4.24m/min.
Analysis of Variance for R2 (Tangential Cutting Force)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	534.881	534.881	59.4312	25.52	0.000
Linear	3	505.651	9.516	3.1719	1.36	0.065
Square	3	19.772	19.772	6.5907	2.83	0.048
Interaction	3	9.458	9.458	3.1528	1.35	0.068
Residual Error	50	116.452	116.452	2.3290		
Lack-of-Fit	5	73.286	73.286	14.6572	15.28	0.000
Pure Error	45	43.167	43.167	0.9593		
Total	59	651.333				

R-Sq = 85.1%

For cutting speed 18.37m/min.
Analysis of Variance for R2 (Tangential Cutting Force)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	249.182	249.182	27.6869	43.71	0.000
Linear	3	228.757	228.757	76.2523	120.39	0.000
Square	3	15.592	15.592	5.1973	8.21	0.000
Interaction	3	4.833	4.833	1.6111	2.54	0.067
Residual Error	50	31.668	31.668	0.6334		
Lack-of-Fit	5	7.390	7.390	1.4780	2.74	0.030
Pure Error	45	24.278	24.278	0.5395		
Total	59	280.850				

R-Sq = 88.7%

For cutting speed 27.95m/min.
Analysis of Variance for R2 (Tangential Cutting Force)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	189.612	189.612	21.0680	23.42	0.000
Linear	3	173.127	9.744	3.2481	3.61	0.019
Square	3	13.360	13.360	4.4535	4.95	0.004
Interaction	3	3.125	3.125	1.0417	1.16	0.335
Residual Error	50	44.988	44.988	0.8998		
Lack-of-Fit	5	21.210	21.210	4.2420	8.03	0.000
Pure Error	45	23.778	23.778	0.5284		
Total	59	234.600				

equations of tangential cutting force for different cutting speed.

(i) The equation for tangential cutting force at cutting speed 4.24 m/min is represented as $R2 = 26.0572 – 1.9883X1 – 0.008X2 + 8.4286X3 – 2.19X3^2 + 0.0019X1X2 + 0.0189X1X3 – 0.0011X2X3$

(ii) The equation for tangential cutting force at cutting speed 18.37 m/min $R2 = 17.5984 + 2.3365X1 + 0.0235X2 + 0.3517X3 + 0.574X1^2 + 0.1625X2^2 – 0.742X3^2 + 0.25X1X2 - 0.6617X1X3 – 0.3338X2X3$

(iii) The equation for tangential cutting force at cutting speed 27.95 m/min $R2 = 103.208 – 0.047X1 - 0.177X2 + 0.535X3 – 0.007X1^2 + 1.137X3^2 + 0.001X1X2 + 0.094X1X3 – 0.006X2X3$

From these equations we can predict the tangential cutting force at different cutting speeds and against the input process parameters, compaction (X1), sintering temperature (X2) & sintering time (X3).

RESULTS AND DISCUSSION

Studies on machinability of sintered P/M components have attracted substantial research interest in contemporary manufacturing technology. This issue has been addressed in a number of previous communications. Some of the researchers investigated machinability in porous iron components (Šalak *et al.*,2005). In the present study we focus on machinability of sintered P/M components through the measurement of cutting forces at various cutting speeds. At the cutting speed of 4.24m/min the nature of variation of Tangential cutting force (R2) is illustrated in (Figs. 1-3). The tangential cutting force is strongly influenced by the variation of compaction (X1), sintering time (X3) and sintering temperature (X2). When the cutting speed is increased to 18.37m/min. the nature of variation (Figs. 4–6) of tangential cutting force against compaction and sintering temperature remains similar to that obtained at the cutting speed of 4.24m/min. This features are compared in figures 1 and 4. However, variation of tangential cutting force against simultaneous variation of sintering time and sintering temperature (Fig. 5) are different from that observed at cutting speed 4.24m/min. Similarly, the response parameter like tangential cutting force shows almost consistent behavior when the sintering time and compaction are chosen as variables (Fig. 6). In this perspective, it is worth mentioning that in each cutting speed, tangential cutting force is also influenced by all the three parameters.

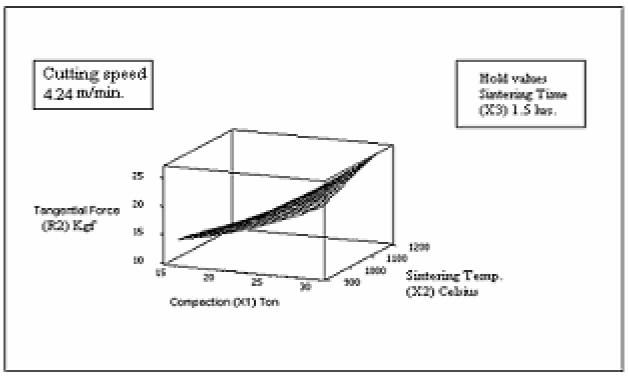

Fig.1. Surface Plot of Tangential Force R2vs Sintering Temp.(X2), Compaction(X1).

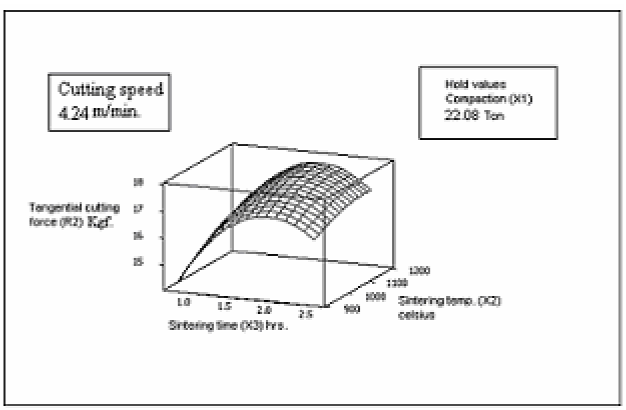

Fig. 2. Surface Plot of Tangential Force R2vs Sintering Temp.(X2), Sintering time(X3).

We notice some intriguing feature in the variation of tangential cutting force against compaction load (X1), sintering temperature (X2) and sintering time (X3). The cutting force gradually increases with the increase in compacting load (X1) and sintering temp (X2). In addition, we noticed that in general, samples sintered at lower sintering time (X3) produces higher cutting force under relatively higher sintering temperature. Moreover, tangential cutting force shows increasing tendency with the simultaneous increase of sintering time and compaction load.

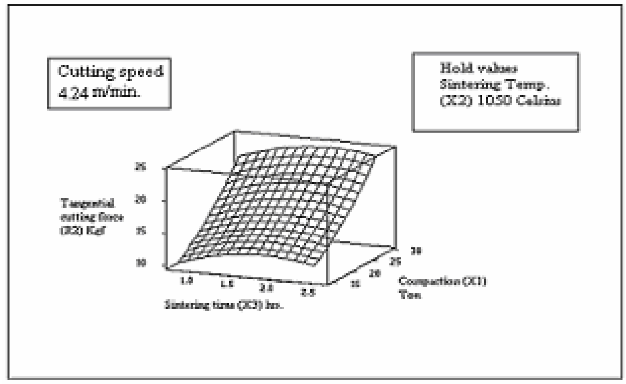

Fig. 3. Surface Plot of Tangential Force R2vs Compaction (X1), Sintering time (X3).

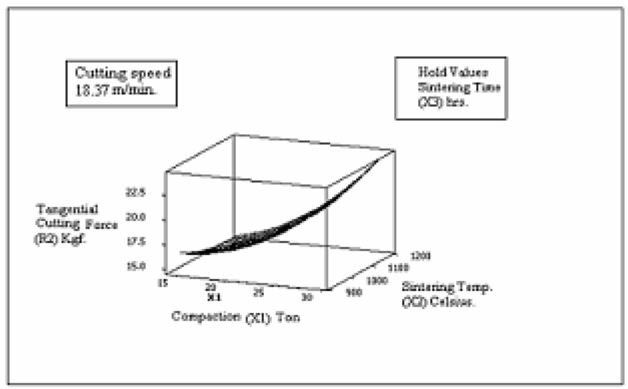

Fig. 4. Surface Plot of Tangential Force R2vs Sintering Temp. (X2), Compaction(X1).

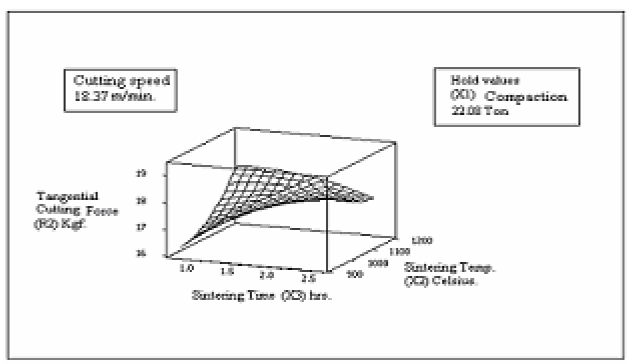

Fig. 5. Surface Plot of Tangential Force R2vs Sintering Temp. (X2), Sintering Time (X3).

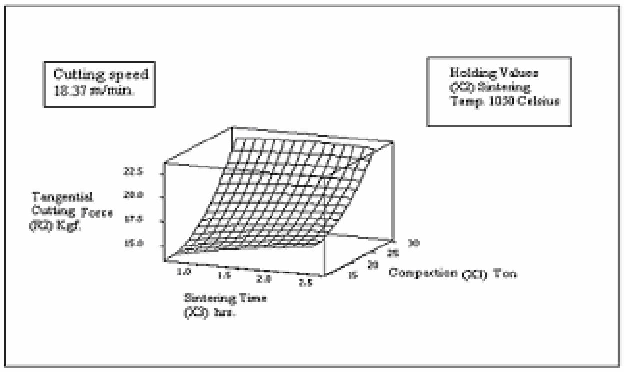

Fig. 6. Surface Plot of Tangential Force, R2vs Compaction (X1), Sintering time (X3).

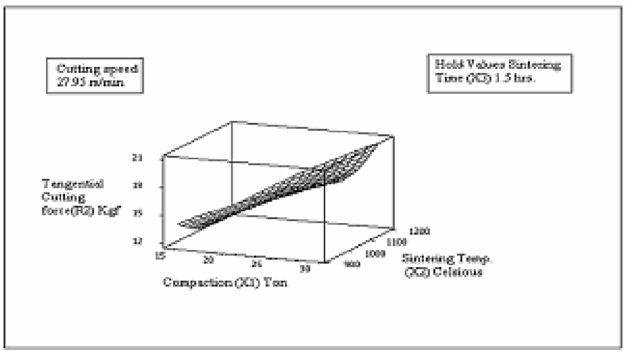

Fig. 7. Surface Plot of Tangential Force R2vs Sintering Temp. (X2), Compaction (X1).

Nature of variation of tangential cutting force at the cutting speed of 27.95 m/min. is depicted in (Figs. 7-9). The figure illustrates a gradual increase in tangential cutting force due to increase of compaction load and temperature. The nature of variation of tangential cutting force against sintering time and compaction load are analogous to that of (Fig. 7). However, it is observed that completely distinct behavior in the variation of tangential cutting force against sintering time and temperature.

A systematic experimental study was performed on the machinability of 60 different sintered P/M iron samples based on DOE. The tangential cutting force was measured during the machining of the above samples under various cutting speeds. Results obtained during experimentation have been analyzed through response surface methodology. Our study reveals that at each cutting speeds, the tangential cutting force is strongly influenced by the variations of sintering temperature, sintering time and compaction. These studies have also revealed that during machining sintered P/M components, the magnitude of tangential cutting force is determined by different external features like compaction load, sintering temperature and sintering time. The Table 3 presents the ANOVA (Analysis of variances) for the second order response surface equations, which quite clearly show that second order response surface model fit well into the observed data. This is evident from the findings that co-efficient of determination (R^2) values are between 82 and 88%. Hence, it may be concluded that the prediction made by this developed model corroborates well with experimental observations. It is expected that the present study will of great importance to the professionals as well as the academicians working in this area.

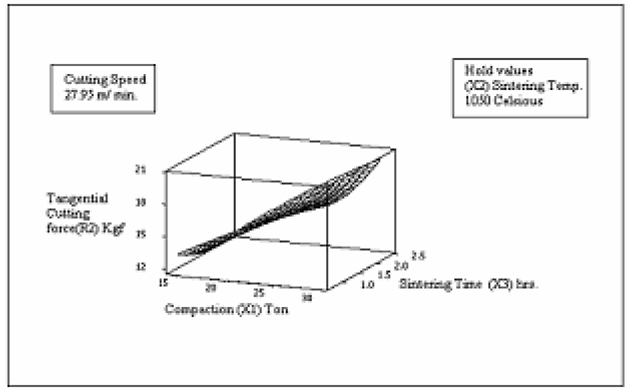

Fig. 8. Surface Plot of Tangential Force R2vs Sintering Time (X3), Compaction (X1).

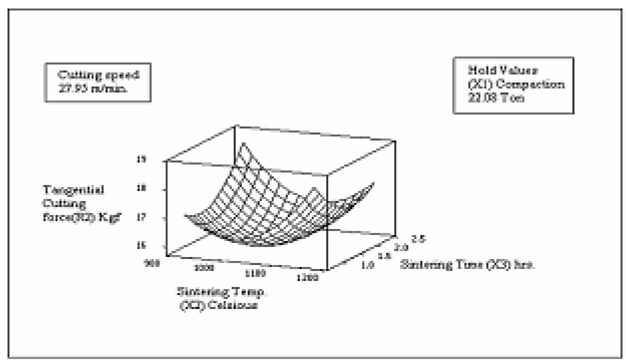

Fig. 9. Surface Plot of Tangential Force R2vs Sintering Time (X3), Sintering Temp.(X2).

CONCLUSIONS

A 2^3 full factorial design of experiments (DOE) have been used to perform statistical analysis of the effect of various process parameters on the machinability of sintered iron P/M component. Second order response surface method (RSM) have been used to develop the predicting equations of cutting force based on the data collected using a statistical design of experiments known as central composite design (CCD) for different cutting speeds. Analysis of variance (ANOVA) presented in Table 3 show that the observed data fits well into the assumed second order RSM model. The surface plots of response surfaces show the existence of optimum values of process parameter for different cutting force of sintered iron components. For the same cutting speed the tangential cutting force is influenced by all the three input processes parameters (X1, X2 & X3). At a relatively higher cutting speed also the tangential cutting force shows similar behavior as in the case of simultaneous variation of compaction, sintering temperature & sintering time. It is worth mentioning that the overall development of new P/M components also requires a thorough analysis of hardness of material against the external variables which we plan to report in our future communication.

Fig. 10. Hydraulic press (120 Ton).

Fig. 11. Tubular vacuum furnace (1450°C).

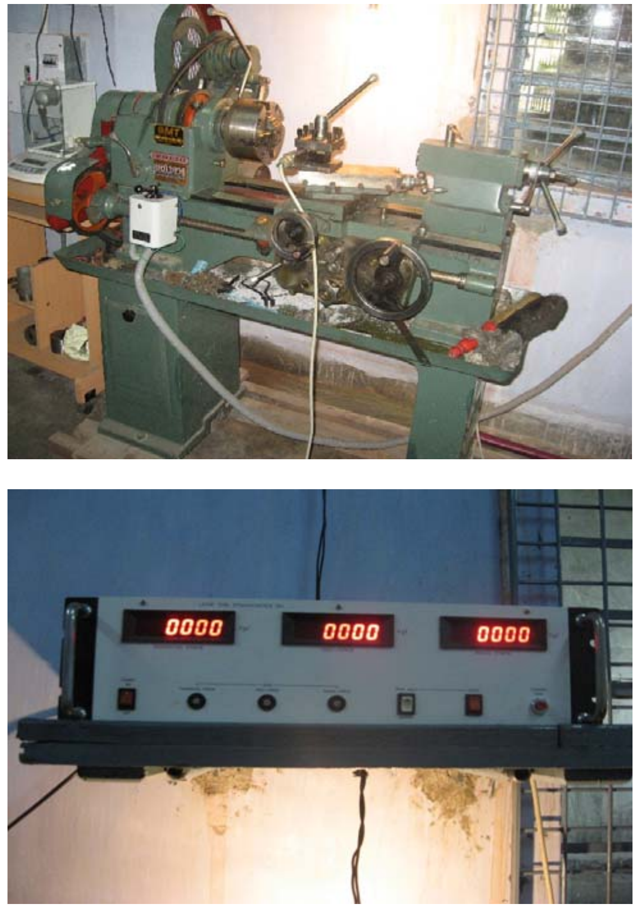

Fig. 12. Lathe with Tool dynamometer Force display unit.

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Nomenclature

α distance from the centre point of the design to a star point (*star arm*)

$\mathbf{B_1}$ $[\hat{\beta}_o\ \hat{\beta}_1\ \hat{\beta}_2\ \hat{\beta}_3\ \hat{\beta}_{12}\ \hat{\beta}_{13}\ \hat{\beta}_{23}\ \hat{\beta}_{123}]^T$

$\mathbf{B_2}$ $[\hat{\beta}_o\ \hat{\beta}_1\ \hat{\beta}_2\ \hat{\beta}_3\ \hat{\beta}_{11}\ \hat{\beta}_{22}\ \hat{\beta}_{33}\ \hat{\beta}_{12}\ \hat{\beta}_{13}\ \hat{\beta}_{23}]^T$

β_o *free term* of the regression equation

β_i regression coefficient of ith process parameter (*linear terms*)

β_{ij} regression coefficient of interaction between ith and jth process parameters (*interaction terms*)

β_{ii} regression coefficient of self interaction of *i*th process parameter (*quadratic terms*)
β_{ijk} regression coefficient of interaction among *i*th, *j*th and *k*th process parameters
$\hat{\beta}_o$ estimated value of β_o
$\hat{\beta}_i$ estimated value of β_i
$\hat{\beta}_{ij}$ estimated value of β_{ij}
$\hat{\beta}_{ii}$ estimated value of β_{ii}
$\hat{\beta}_{ijk}$ estimated value of β_{ijk}
E(x) mathematical expectation of the variable *x*
E an error component
R2 Tangential Cutting Force
Ŕ2 Average value of Tangential Cutting Force
K number of controllable process parameters
l number of levels for each process parameter
m number of coefficients in the regression equation
N total number of design points = $n_f + n_a + n_c$
n_a number of axial points = 2*k*
n_c number of central points
n_f number of points used in factorial positions = 2^k
σ_β^2 variance of regression coefficients
σ_{res}^2 residual variance
σ_e^2 estimate of error (replication variance)
$t_{estimated}$ estimated *t* value
$t_{\alpha_s, \nu}$ value of Students *t* distribution for α_s level of significance and ν degrees of freedom
X a matrix formed by column vector $\mathbf{x_o}$, $\mathbf{x_1}$, $\mathbf{x_2}$, $\mathbf{x_3}$,…..etc
$\mathbf{X^T}$ transpose of the matrix **X**
x_i coded value of *i*th process parameter
$\mathbf{x_o}$ column vector of dummy variable i.e column of 1' s
$\mathbf{x_i}$ column vector of coded values for process parameter x_i
$\mathbf{x_{ij}}$ [scalar product of column vectors $\mathbf{x_i}$ and $\mathbf{x_j}$]
$\mathbf{x_{ijk}}$ [scalar product of column vectors $\mathbf{x_i}$, $\mathbf{x_j}$ and $\mathbf{x_k}$]
z_i actual value of *i*th process parameter
z_i^{max} maximum actual value of the *i*th process parameter
z_i^{min} minimum actual value of the *i*th process parameter
z_i^o centre point of the design or the basic level of the *i*th process parameter
Δz_i unit or interval of variation on the z_i axis for the *i*th process parameter.

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