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Prediction of hardness for sintered HSS components using response surface method

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Abstract

Sintered high speed steel (HSS) components have been formed using powder metallurgy (PM) process. Water-atomized and vacuum—annealed powders of T-15 grade HSS along with other ingredients like Zn-stearate (2%) and alumina (Al_2O_3) were used to produce the components. The percentage of alumina, sintering temperature and sintering time were considered as the controllable process parameters while the hardness of the sintered components was considered as the response variable. A 2^3 full factorial design of experiments (DOE) was used to collect experimental data to statistically analyze the effect of process parameters on the hardness of sintered HSS components. It has been observed that the percentage of alumina, sintering temperature and also their interaction affects the hardness very significantly while duration of sintering temperature does not affects the hardness significantly. A second order response surface model (RSM) has been used to develop a predicting equation of hardness 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 RSM model.

Keywords: Sintered components; Response surface; Central composite design; *t*-Test; *F*-Test

1. Introduction

Powder metallurgy (PM) HSS bar is well-established in Europe, USA and Japan as the main root of production of gear hubs, end mills, cold pressing dies and other high pressing tools. Titanium nitride and Titanium carbide coating processes have significantly increased tool life in many applications, while this has brought significant savings to the final customers. In the 1970s and early 1980s, massive rationalization took place world wide in the High Speed Steel Industries [1–8]. Tool users became more cost conscious and premature tool failures were no longer tolerated. It was realized several years before by the PM HSS components makers that with advances in conventional machining processes and the reduction in prices of conventional bar, component would only sell which had sufficient dimensional accuracy to avoid machining and which were totally repeatable in metallurgical quality. As a result the trend on PM HSS followed that of hard metals away from the large complex shaped components towards the index able inserts. It has been reported that 1–3% alumina addition during compaction enhances the tool life of the PM HSS cutting tool inserts.

In this study, an attempt has been made to develop a PM HSS cutting tool material with high hardness by improving the micro-structure as well as superior homogeneity with uniformly distributed carbides with uniform and finer grain size which results the PM HSS comparable with other hard metals like carbides in all respect [9–12]. Design of experiments (DOE) have been used to perform statistical analysis about the effect of various process parameters on the hardness of sintered HSS components and response surface method has been used to develop a predicting response surface equation for hardness of sintered HSS component.

2. Experimental procedures

The HSS powder of T-15 grade was supplied by M/S Hoganas Limited (Great Britain) and the chemical analysis was carried out by Powdrex in Great Britain. Leco Analyser and Hilger Polyvac were used for performing the analysis. The result of chemical analysis of T-15 grade HSS powder has been given in Table 1 (all data are in percentage of weight except where stated).

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Nomenclature

$\mathbf{B}_1$	$[\hat{\beta}_0\ \hat{\beta}_1\ \hat{\beta}_2\ \hat{\beta}_3\ \hat{\beta}_{12}\ \hat{\beta}_{13}\ \hat{\beta}_{23}\ \hat{\beta}_{123}]^{\mathrm{T}}$
$\mathbf{B}_2$	$[\hat{\beta}_0\ \hat{\beta}_1\ \hat{\beta}_2\ \hat{\beta}_3\ \hat{\beta}_{11}\ \hat{\beta}_{22}\ \hat{\beta}_{33}\ \hat{\beta}_{12}\ \hat{\beta}_{13}\ \hat{\beta}_{23}]^{\mathrm{T}}$
$E(x)$	mathematical expectation of the variable x
$F_{\mathrm{estimated}}$	estimated value of Fisher's F-ratio
$F_{\alpha_{\mathrm{s}},\nu_1,\nu_2}$	Fisher's F-ratio for ν_1 upper and ν_2 lower degrees of freedom for α_{s} level of significance
H	Hardness of sintered components
$\bar{H}$	Average value of hardness
$\bar{H}_i$	Average value of hardness for ith run number
$\bar{H}_{\mathrm{oci}}$	Average value of hardness for central points
$\bar{\bar{H}}_{\mathrm{c}}$	Average of averages of hardness values for central points
k	number of controllable process parameters
l	number of levels for each process parameter
m	number of coefficients in the regression equation
n_{a}	number of axial points = $2k$
n_{c}	number of central points
n_{f}	number of points used in factorial positions = 2^k
N	total number of design points = $n_{\mathrm{f}} + n_{\mathrm{a}} + n_{\mathrm{c}}$
$t_{\mathrm{estimated}}$	estimated t value
$t_{\alpha_{\mathrm{s}},\nu}$	value of Students t distribution for α_{s} level of significance and ν degrees of freedom
$\mathbf{X}$	a matrix formed by column vector $\mathbf{x}_0$, $\mathbf{x}_1$, $\mathbf{x}_2$, $\mathbf{x}_3$, . . ., etc.
$\mathbf{X}^{\mathrm{T}}$	transpose of the matrix $\mathbf{X}$
x_i	coded value of ith process parameter
$\mathbf{x}_0$	coloum vector of dummy variable i.e. column of 1's
$\mathbf{x}_i$	coloum 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 ith process parameter
$z_i^{\max}$	maximum actual value of the ith process parameter
$z_i^{\min}$	minimum actual value of the ith process parameter
z_i^0	centre point of the design or the basic level of the ith process parameter
Δz_i	unit or interval of variation on the z_i axis for the ith process parameter

Greek letters

α	distance from the centre point of the design to a star point (star arm)
β_0	free term of the regression equation
β_i	regression coefficient of ith process parameter (linear terms)
β_{ii}	regression coefficient of self interaction of ith process parameter (quadratic terms)
β_{ij}	regression coefficient of interaction between ith and jth process parameters (interaction terms)
β_{ijk}	regression coefficient of interaction among ith, jth and kth process parameters
$\hat{\beta}_0$	estimated value of β_0
$\hat{\beta}_i$	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}
ε	an error component
σ_{e}^2	estimate of error (replication variance)
σ_{res}^2	residual variance
σ_{β}^2	variance of regression coefficients

Table 1
Chemical Analysis of T-15 grade HSS powder

C	Co	Cr	V	W	Si	P	Mn	Mo	S	O (ppm)
1.605	5.03	3.92	4.82	12.02	0.36	0.01	0.23	0.8	0.018	733

Powder properties

Apparent density (gm/cm^3)	2.24
Flow (s/50 gm)	39.72
Compressibility (gm/cm^3)	5.96
Green strength (psi)	3059

Sieve distribution

Sieve number	Size (μm)	Cumulative (wt%)
+60#	>250	0.00
+85#	>180	0.00
+100#	>150	0.01
+150#	>106	9.29
+200#	>75	28.55
+350#	>45	62.15

The powder was compacted in a closed square die (as the shape of the square inserts) using 150 tonnes capacity hydraulic press. The die wall was lubricated with zinc stearate and the compacts were prepared according to a planned statistical design of experiments and the relative density of sintered performs were measured by hydrostatic process and the surface of the specimens was then polished with a fine emery paper. Hardness was determined by Rockwell Hardness tester using Scale B.

3. Effect of process parameters on hardness

In order to perform test of significance for individual process parameters as well as their interactions, an equation that can be considered is given by the following expression [14]:

$$\bar{H} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \beta_{123} x_1 x_2 x_3 + \varepsilon, \quad (1)$$

and the corresponding fitted equation can be expressed as follows:

$$\begin{aligned}\hat{\bar{H}} &= E(\bar{H} - \varepsilon)\\ &= \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_3 x_3 + \hat{\beta}_{12} x_1 x_2 + \hat{\beta}_{13} x_1 x_3 + \hat{\beta}_{23} x_2 x_3 + \hat{\beta}_{123} x_1 x_2 x_3.\end{aligned} \quad (2)$$

where $E(x)$ is the mathematical expectation of the variable x.