NANO-LEVEL SURFACE GENERATION ON H13 ALLOY STEEL BY ULTRA-PRECISION GRINDING WITH ELECTROLYTIC IN-PROCESS DRESSING

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ABSTRACT

The aim of this work was to achieve the surface finish of 10nm on a 40mm diameter disc of chrome-molybdenum-vanadium alloyed steel (H13) by using precision grinding process with electrolytic in-process dressing. The machine tool utilized was Tetraform-C, its unique tetrahedral frame offered higher structural stability. A cup grinding wheel with iron bonded CBN abrasive grit of 76 microns average size with 50% concentration was used. The statistical methods were employed to determine the optimal combination of input parameters to achieve the required response. The main effect of feed rate was found to be more significant than the depth of cut and lower levels of these factors produced better surface finish. The developed regression model based on the relationships between process variables was used to predict factor levels to achieve the required process response.

Keywords: Ultra precision grinding, electrolytic in-process dressing, optimization.

1 INTRODUCTION

With the increasing applications of hard to machine materials such as advanced ceramics, super alloys, and the increased accuracy requirements on a work piece, metal bonded super-abrasive (diamond and cubic boron nitride) grinding wheels are getting widespread attention in industry because of their form accuracy and cutting ability in grinding (Chen 1998). The metal bonds are made from sintered metallic powders having high stiffness, excellent form holding characteristics, a high impact resistance and a good durability. For industrial applications, the super-abrasive wheels should be dressed automatically during grinding operation. Because the low chip load of metal bonded wheels, the high contact area between wheel and work, and the reduced machine stiffness may cause diminished bond erosion. Without a proper dressing operation even the most precise grinder cannot fully take the advantage of the super-abrasive potential (Chen 1998).

Grinding with electrolytic in process dressing (Elid) was first proposed by the Japanese researcher Hitoshi Ohmori (Ohmori and Nakagawa 1990). It is a grinding process that employs metal bonded abrasive wheels continuously in-process dressed by the means of electrolysis. The electrolysis removes the metal

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bond and worn diamond particles, to expose the fresh diamond grits, and to restore efficiency during grinding operation. Reportedly, Elid successfully assisted during grinding of components made out of various brittle materials (Ceramics, hard steels, etc) of different shapes and dimensions (Ohmori and Nakagawa 1995). For many of these applications, Elid assisted in eliminating final polishing or lapping operations. Over the years the process has been studied worldwide indicating the achievable benefits by the use of this technology (Inasaki, Tonshoff and Howes 1993; Lee and Kim 1997; Ohmori and Nakagawa 1997; Ohmori, Takahashi and Bandyopadhyay 1996a&b; Pavel 2004; Suzuki et al. 1991).

The key factors enabling the exploitation of Nano-grind technology on metallic components are the tribological aspects of low friction and wear rates. The aim of this work was to achieve the surface finish of 10nm on a 40mm diameter disc of H13 alloy steel by using elid assisted precision grinding technique. The statistical methods were employed to determine the optimal combination of input parameters to achieve the required response.

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1 Specimen Material

The material of the specimen was chrome-molybdenum-vanadium alloyed steel (H13) with following chemical composition:

Table 1: Chemical Composition of H13

C	Si	Mn	Cr	Mo	V
0.37 ~ 0.42 %	0.85 ~ 1.20 %	0.20 ~ 0.50 %	5.0 ~ 5.50 %	1.20 ~ 1.70 %	0.85 ~ 1.20 %

The features of this steel are:

- High resistance to thermal shock and heat cracking
- Good toughness in hot condition
- Constant hardness throughout the production cycle
- Excellent machinability

2.2 Precision Machine Tool

The machine tool utilized for the experiments was Tetraform C, which was developed in 1999, with its unique tetrahedral frame for higher structural stability (both static and dynamic). The machine is equipped with a vertical grinding spindle and linear X - Y axes. The figure 1 shows the general arrangement of the machine tool.

Figure 1: Precision machine tool (Tetraform C).

2.3 Grinding Wheel and Specimen Holding Arrangement

The grinding wheel used for the experiments was a cup wheel with metal bonded (iron) CBN abrasive grit (grit average size of 76 microns and concentration of 50%). The grinding wheel consisted of a steel ring structure on which eight segments (4mm of width) of Iron-CBN composite were mounted. The steel base ring of the grinding cup wheel was provided with threaded holes on the periphery where weights (grub

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screws) could be added for accurate dynamic balancing. The grinding wheel was trued in a way that an acute edge at the bottom face of each segment was generated. The spindle head was dynamically balanced after truing and a spindle run out of less than 0.03 microns was achieved at 6000rpm.

The procedure adopted for holding specimen on the machine involved heating of the holding plate on a hot plate for approximately 3 to 4 minutes. After that period wax was applied over an area approximately equal to the diameter of the specimen in the middle of the holding plate. The specimen was placed and held down over the waxed area to squeeze out excessive wax between the surfaces. The plate and the specimen were then allowed to cool down. Afterwards, the holding plate was bolted onto the holding block already mounted on the rotary table of the machine. The requirement for peripheral holding of the specimen was realized during the initial grinding trials due to the movement of the specimen during operation. Therefore, two V-shaped fixtures were introduced, which could be bolted onto the holding plate for fixing the specimen (figure 2).

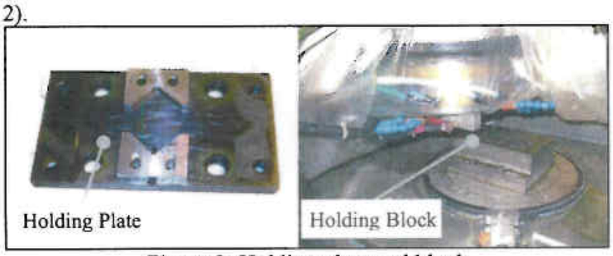

Figure 2: Holding plate and block

2.4 Elid Setup

To supply electrical energy, a copper spring plate was setup to be in mechanical contact with the periphery of the grinding wheel on one end while the other end was connected to the positive terminal of the DC supply, thereby making the grinding wheel an anode. The grinding cup wheel was supplied with a steel base ring, which was attached to the main machine spindle through an insulating polymer ring. The insulating polymer ring was used for restricting the electrical supply, to avoid any damage to the main spindle and other components but more importantly for the safety in use. The negative terminal of the supply was connected to the copper plate (cathode), which was mounted on insulated holding block such that a gap of approximately 0.3mm was maintained between the copper plate and the bottom face of the grinding wheel.

Figure 3: Elid Setup

The electrical supply used was Fuji Elider (ED 921) with following possible settings;

- Peak Voltage (V_p): 60 to 90 Volts
- Peak Current (I_p): 20 to 40 Amperes
- Duty Ratio: 10% to 70%

Where;

$$Duty\ Ratio\ (\%) = \frac{t_{on}}{t_{on} + t_{off}} \times 100$$

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't_{on}' and 't_{off}' are the 'On' and 'Off' time for the square DC pulse generated by the supply. The coolant used was water soluble, medium duty, fully synthetic oil (Dowel, UK). An aqueous solution with 2% dowel was prepared for the experimentation.

2.5 Determination of Surface Speed for Elid Assisted Grinding

The consistency and efficiency of Elid grinding are currently realized at a low surface speed of grinding wheels. The reason for this behaviour is that the dressing efficiency drops at high surface speeds and a dull grinding wheel can no longer be sharpened (Bifano et al. 1995). Very little guidance can be obtained from literature on elid parameters, specifically surface speed for selected cup grinding wheel. Therefore, to determine the optimal rotational speed for efficient elid assisted grinding operation, experiments were conducted to measure dressing current and voltage values at different rotational speeds of grinding wheel and at different duty ratios.

The initial dressing was carried out at 500rpm with a peak voltage of 60volts and peak current of 20amps. Dressing voltage and current were monitored and after 20mins of operation saturated dressing voltage and current values were achieved. This indicated that the maximum resistance has been established through the development of maximum thickness of oxide layer, for the set of Elid parameters. The figure below shows the dressing voltage and current values plotted against dressing time.

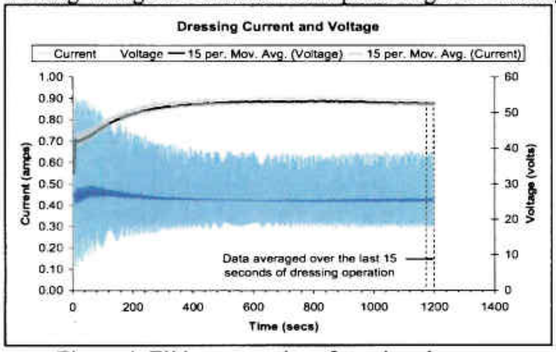

Figure 4: Elid power values for a dressing run.

The reason for carrying out the dressing operation at 500rpm and lower duty ratio is to have a stable and consistent growth of oxide layer to achieve the maximum resistance, which in turn would give stable dressing voltage and current that could be used as reference for comparing dressing currents at different rotational speeds. Dressing current at different rotational speeds was used as a measure of electrolysis. Where drop in current value would indicate increase in Elid circuit resistance for a particular set of Elid parameters (peak voltage, peak current and duty ratio).

Each subsequent run at different rotational speeds was carried out for the duration of 30 seconds, to ascertain the variation in dressing current values. The selected duration was just enough for the machine spindle to reach stable speed, to inhibit possible further growth of oxide layer that could change the resistance and allow at least 15 seconds of data to be averaged and compared. The table below shows the effect of rotational speed on the measured dressing current at different duty ratios. Where 6000 rpm was the maximum achievable spindle speed for the Tetraform machine.

Table 2: Effect of Rotational Speed on Dressing Current

Run#	Avg. Time (secs)	RPM	Peak Voltage (volts)	Peak Current (amps)	Duty (%)	Pulse Type	Dressing Current (amps)
1	15	500	60	20	10	Square	0.416
2	15	6000	60	20	10	Square	0.338
3	15	500	60	20	30	Square	0.416
4	15	6000	60	20	30	Square	0.332

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5	15	500	60	20	50	Square	0.417
6	15	6000	60	20	50	Square	0.332

It can be observed that there is a marked reduction in dressing current with increase in rotational speed. This reduction in dressing current is indicative of increase in resistance for the same Elid parameters (peak voltage, peak current, duty ratio and gap). Thus signifying insufficient electrolyte flow in the dressing zone.

Insufficient electrolyte supply in the dressing zone could be attributed to the high relative speed between the cathode and the grinding wheel. This high relative speed prevents electrolyte from reaching the wheel. For the electrolyte to reach the high speed wheel surface, it should have a pressure high enough to penetrate the air film initially and then maintain adequate pressure inside the dressing zone. Increasing supply pressure can generate enough momentum in electrolyte to overcome the centrifugal force and reach the wheel surface. Current supply pressure cannot provide enough momentum to overcome the centrifugal force and reach the wheel surface at high pressure. Although a special cathode that could supply electrolyte directly into the dressing zone was introduced but it didn't offer any improvement and it still had problem at high speed owing to its structure and the supply direction. Therefore, lower rotational speed of grinding wheel had to be preferred during the grinding operation for elid to be efficient.

2.6 Grinding Parameters and Surface Integrity

The higher power values (voltage and current) for Elid would result in higher dissolution of the bonding metal of the grinding wheel consequently increasing the grit removal rate. As mentioned previously, a cup grinding wheel with an average grit size of 76 microns was used; therefore, the probability of dislodging a bigger grit size from its post, at a higher Elid power is more than that at lower power values. Hence lower levels for duty ratio (10%), voltage (60V) and current (20A) were used during experimentation. Whereas the rotational speed of 3000rpm was kept fixed, feed and depth of cut (DOC) were varied to achieve the required surface finish (SF).

Another problem faced during these trails was that the surface finish could not be measured after each single run to ascertain the effect of process parameters. Primary reason being that the removal of specimen by detaching the holding plate from the machine would not only induce parallelism error but also the time required for that was significant to affect the spindle growth mechanism requiring machine warm-up procedure (time required approximately two hours) to be repeated. In the given situation a standard was formulated based on visual inspection for qualitative assessment of the surface finish (Table 3).

Table 3: Standard Formulated for Visual Inspection of Surface Finish (SF)

S/No.	Standard	Description
1	100% of the surface scratched	Thin and thick scratches over the entire surface
2	75% of the surface scratched	Majority of the surface with thick scratches
3	50% of the surface scratched	Half of the surface with thick and thin scratches
4	25% of the surface scratched	Localized thin scratches
5	10% of the surface scratched	4-6 thin scratches over the entire surface
6	Less than 10% of the surface scratched	2-3 thin scratches over the entire surface

Based on the above standard the surface finish of 10% or less was considered reasonable, and the component could be taken out for quantitative assessment by using Taylor Hobson (TeleSurf).

2.7 DOE and Parameter Optimization

No experimental data was available for a specimen of given material, hardness and dimensions, machine input and Elid parameters, therefore, initial grinding trials were conducted based on the experience. However, during these runs it became clear that the required surface finish (< 10nm) could only be achieved through the use of statistical techniques.

The (statistical) design of experiments (*DOE*) is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions (Anthony et al. 2003). The

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task starts with identifying the input variables and the response (output) that is to be measured. For each input variable, a number of levels are defined that represent the range for which the effect of that variable is desired to be known.

The objective was to achieve the required surface finish (<10nm) on a specimen of diameter 40mm with a cup grinding wheel of 76microns grit size (CBN), a factorial experiment with two factors (Feed and DOC) at two levels with one possible interaction was designed that required the minimum number of runs. The runs were replicated (x2) to cancel the noise effect and the run order was randomized to lessen the effects of other factors that were not included in the study (Engineering Statics Handbook). The table below shows the selected low and high values for the considered factors and the designed matrix in coded units against which the process response was monitored.

Table 4: Factor levels and the designed factorial matrix

Factors		**Low**			**High**	
Feed (mm/min)		4			10	
DOC (microns)		4			20	
Std Ord	**Run Ord**	**Centre Pt**	**Feed**	**DOC**	**Feed x DOC**	**Surface Finish (SF)**
1	1	1	-1	-1	1	25%
4	2	1	1	1	1	50%
6	3	1	1	-1	-1	75%
2	4	1	1	-1	-1	75%
3	5	1	-1	1	-1	35%
5	6	1	-1	-1	1	35%
8	7	1	1	1	1	50%
7	8	1	-1	1	-1	50%

3 RESULTS AND DISCUSSION

3.1 Analysis of Variance

The data was analysed using the Minitab software, the details are summarized below:

Table 5: ANOVA and estimated regression coefficients

Analysis of Variance				
Source	**Degrees of Freedom**	**Sum of Squares**	**Mean Squares**	**P-value**
Main Effects	2	0.14562	0.072812	0.010
2-Way Interactions	1	0.07031	0.070312	0.014
Residual Error	4	0.01625	0.004062	
Total	7	0.23219		
Estimated Effects and Coefficients (coded units)				
Term	Effect	Coefficient	Standard Error	P-value
Constant		0.49375	0.02253	0.000
Feed	0.26250	0.13125	0.02253	0.004
DOC	-0.06250	-0.03125	0.02253	0.238
Feed x DOC	-0.18750	-0.09375	0.02253	0.014
Estimated Coefficients (uncoded units)				
Constant	--	-0.09375	--	--
Feed	--	0.09063	--	--
DOC	--	0.02344	--	--
Feed x DOC	--	-0.00390	--	--

From the ANOVA table the p-values for the main effects and 2-way interaction suggest that both the main effects and interactions are significant. However, the relative strength of the effects as indicated in the Effect column suggests that the feed has the greatest effect (0.2625) on the surface finish and the interaction between the feed and DOC can be ranked as the second greatest effect (-0.1875). To visualize the main effects and interaction plots were produced based on the means of the response data. The figure below shows the main effects plot for feed and DOC. Clearly, feed has larger main effect than DOC, indicated by the steeper slope of the line connecting the mean responses at the low and high settings of feed rates.

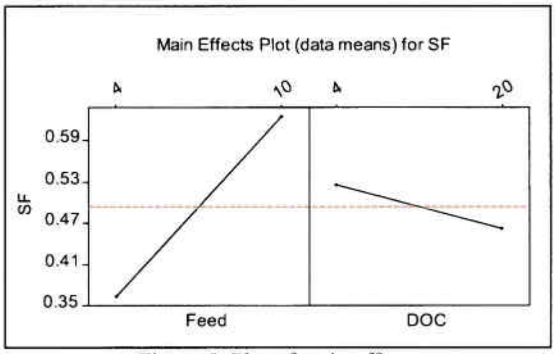

Figure 5: Plot of main effects

Although the feed rates appear to affect the response more than the DOC, it is very important to look at the interaction because an interaction can magnify or cancel out a main effect. The figure below shows an interaction plot between feed and DOC:

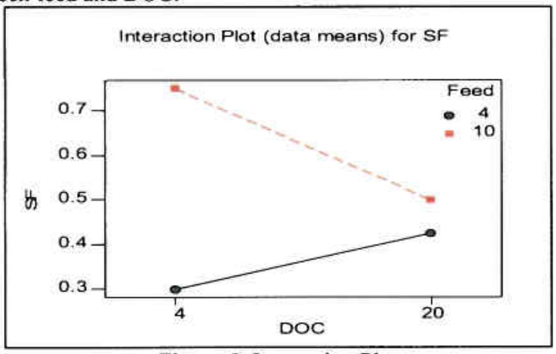

Figure 6: Interaction Plot

It can be observed from the above plot that the lower levels of both the factors, that is, the depth of cut and feed rates would produce better surface finish. However, the surface finish produced by lower levels of these factors was ranked as 30% by visual inspection and would not meet the requirement of <10nm (Ra). Further improvement in surface finish by varying feed and depth of cut were investigated by using the regression model.

3.2 Fitted Regression Model

The regression equation in uncoded format (table 5) based on the relationship between the factors, their interaction and the response is given below.

$$SF = -0.09375 + 0.09063(feed) + 0.02344(DOC) - 0.004(feed * DOC)$$

The linearity of the regression equation and the plots for main effects and interaction suggest that lower levels of feed and doc would result in better surface finishes. Based on that feed of 2mm/min and doc of 2microns was investigated, the predicted response from the model was around 11% whereas the experimental response was around 10%. The measured surface finish by using the Telesurf was was well within required range. Further, reduction in feed rate (1mm/min) produced better results, however the processing

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time required for a specimen of 40mm diameter specimen at the stated feed rate was more than 40min. Therefore, the feed rate of 2mm/min and doc of 2microns was preferred.

4 CONCLUSIONS

- There is marked reduction in dressing current with increase in rotational speed of the cup grinding wheel and is indicative of increase in resistance for the selected Elid parameters (peak voltage, peak current, duty ratio and gap). Hence signifying insufficient electrolyte flow in the dressing zone.
- The statistical analysis (ANOVA) indicated that main effect of feed rate and the interaction between the feed rate and depth of cut were the most significant factors. Furthermore, lower levels of both the main effects (feed rate and depth of cut) produced better surface finish.
- The regression model based on the relationship between the process variables was found to be effective for the prediction of new factor levels to achieve the required process response.

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We extend a warm welcome to our invited speakers Professor Tim Baines, Professor Raj Roy, Professor Wilhelm Appold, Professor Omkar Mohanty, Mr Vijay Saha, Professor Priyavarat Thareja, Mr Andrew Turner and Dr. Sundara Murthy who will provide valuable insights into the competitive pressures faced by a global economy and the responses needed by all stake holders.

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