Performance Analysis of Cryogenically Treated Vanadis23 Tool under Dry Turning Conditions

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Abstract: In the present investigation, the wear resistance of PM tools in turning operation is studied. The tool steel is subjected to various cryogenic treatments along with the conventional heat treatment. Tool life in a production operation depends on the part geometry and requirements, cutting conditions and in some cases on machine tool and tool holder characteristics hence for realistic estimates of tool life in practice generally be obtained only from production test results or experience. In this paper an attempt is made to study the effect of cryogenic treatment on wear and a proposal of a mathematical model to evaluate the wear of cryogenically treated Vanadis23 PM steel tool. For this Taguchi's OA method is used to finalize the experiments.

Keywords: PM steel tools, cryogenic treatment, wear resistance, Taguchi O. A., empirical mathematical model.

1. INTRODUCTION:

Up till now, many publications investigated DCT of conventionally produced tool steels. But very few attentions have been paid to materials produced by another routes such as powder metallurgical tool steels. The powder metallurgical (PM) method can achieve a more homogeneous microstructure compared to conventionally produced steels. The PM route was chosen because segregation-free and more homogeneous microstructures with a more cleanness can be achieved in comparison to a conventional metallurgical (IM) route. Different mechanical properties can be achieved by PM method which depends on whether samples were taken parallel or perpendicular to the direction of hot deformation. As well, PM tool steels provide uniform spacing between single carbides in all directions [1].

Tool life is a time period in minute between two successive grindings. Tool life is mainly related to the tool wear. Performance of a tool is based on material of tool, work material and cutting conditions or environment. Cutting tools have a limited life because of wear. There are mainly two types of wear related to tool i.e. flank and crater wear. There are various tool materials used in metal cutting industries among them are HSS, alloy steel, cemented carbides, coatings of hard materials, ceramic etc. But HSS is predominantly widely used tool material in industries till date. Flank and crater wear are the most important and thus the most widely measured forms of tool wear. Flank wear is most commonly used for tool wear monitoring since it occurs in virtually all machining operation. F. W. Taylor has been shown the relationship between tool life and cutting speed. Cutting speed, feed and depth of cut are parameters that effect on the tool life. But cutting speed is main factors which affect on the tool life as it produce more heat and increase temperature at cutting zone. As temperature at cutting zone increases wear of tool increases thereby reducing the tool life. An attempt is made in this paper study the performance and to propose a mathematical model to evaluate the wear of cryogenically treated Vanadis23 PM steel tool related to turning parameters. For this Taguchi's orthogonal array method is used to finalize number of experiments [2,3]. Flank wear is the most commonly used norm for determination of tool life of HSS tools [21].

Sub-zero treatment (also considered to as cryogenic treatment) is a method of treatment at low temperatures (lower than -80℃) added to the Conventional Heat Treatment (CHT). Fundamentally it is the extension of standard heat treatment processes. In case of tool steels, cryogenic treatment at temperatures ranging from -140℃ to -196℃, referred to as Deep Cryogenic Treatment (DCT), included between the quenching and tempering is the most commonly used [7].

A. Oppenkowski, et al. [1], the most significant factors which influenced the properties of tool steels were the austenitizing and tempering temperatures during conventional heat treatment. The parameters which were relating to deep cryogenic treatment, the holding time and the heating rate had a significant effect on the material properties. It was seen for a longer holding time of 36 h, the wear rate reaches minimum and increase again on further holding. G. Straffelini et al. [4], the cryogenic treatments induced an improvement in the wear resistance. T.V. Sreerama Reddy et al. [5], the improvement in flank wear resistance was 21.2% and improvement in tool life was 11.1%. The main cutting force was lesser as compared to untreated tungsten carbide inserts and improvement in surface roughness. B. Podgornika et al. [6], the deep-cryogenic treatment improved microstructure of P/M high-speed S390 Microclean from Boehler steel as finer needle-like martensitic structure. This microstructure resulted in higher surface hardness and improved tribological properties, particularly in terms of friction and galling resistance against stainless steel. Sobotova J et al. [7], in case of Vanadis6 steel after DCT there was a slight increase in the wear rate, butVanadis30 did not show any effect of the cryogenic treatment on wear rate. Martin Kurik et al. [8], the bending-strength was nearly identical after the conventional and cryogenic treatment of C/M tool steel 1.2379 and P/M HSS Vanadis23. The strength of steel Vanadis23 was around 1000 MPa higher than that of steel 1.2379 in all the types of heat treatment. But the hardness values for the two reference materials were somewhat decreased after the cryogenic processing. T. V. Sreerama Reddy et al. [9], cryogenic treated tungsten carbide tool tips were subjected to lesser tool wear and there was increase in the tool life, reduced cutting force and gave better surface finish compared to untreated tools. A.Y.L. Young, et al. [10], the cryogenic treatment improved the life span of cutting tools would depend alot on the cutting conditions. Tools under mild cutting conditions had gain from cryogenic treatment, and heavy duty cutting operations with long periods of heating of the cutting tool would not benefit from it. D. Das et al. [11], there was existed an optimum soaking duration for cryo treatment of tool/die steels to achieve the best combination of desired microstructures and wear properties. The optimum soaking time for cryotreatment of AISI D2 steel was around 36 h. D. Das et al. [12], wear resistance of AISI D2 steel increased with increasing holding time up to 36 h at 77K beyond which it showed monotonic decrease with further increase in holding time. A. Akhbarizadeh et al. [13], as there was decrease of the retained austenite percentage in the samples kept for longer periods (40 h instead of 20 h) at shallow cryogenic temperatures, higher wear resistance and higher hardness were observed. Likewise, as a result of the decrease of the retained austenite percentage in the cryogenically stabilized samples (kept at room temperature for 1 week after quenching), the wear resistance and hardness improved, compared with the non-stabilized samples. V. Firouzdor et al. [14], cryogenic treatment affected the entire section of the component unlike coatings; hence similar lives can be expected after each regrinding. Mahdi Koneshlou et al. [15,16], the most important effect of tempering the deep cryogenically treated samples was seen in improving of the wear properties of the H13 tool steel. I. Gunes et al. [17], the cryogenic process increased the wear resistance of the Vanadis4 steel and it was lowest in the DCT-24 h samples tempered at 525°C.

2. BACKGROUND:

The most widely used tool life equation is the Taylor's equation which relates the tool life T in minutes to the cutting speed in m/min through an empirical tool life constant, C [3]:

$$VT^n = C$$

This equation can be expressed as:

$$V\,(TL)^n = C, \qquad (1)$$

where TL, tool life in minutes.

Taylor's equation reflects the main effect of cutting speed on tool life but does not account for the smaller but significant effects of the feed rate and the depth of cut. Therefore a modified version of Taylor's equation, called the extended Taylor equation used [3] is:

$$V(TL)^n f^a d^b = C_1 \qquad (2)$$

where n, a, and b are tool material constants. This equation can be written for tool life as:

$$TL = a_0 \cdot V^{a_1} \cdot f^{a_2} \cdot d^{a_3} \qquad (3)$$

where a_0, a_1, a_2 and a_3 are the constants related to tool-work combinations.

There are various methods to determine tool life data. As suggested by Taylor, if wear land is considered to be constant, the wear-land curves can be extrapolated to determine tool life. An equation can be written for tool life in terms of wear [6] as:

$$TL = \frac{w_1 - w}{k_w} \qquad (4)$$

where w_1 is wear land failure criterion, w is the wear land intercept found experimentally and k_w is wear land growth rate.

Tool wear, w and cutting time, t mathematically can be expressed [20] as:

$$w = w_0 + m.t \qquad (5)$$

where w_0 is initial wear, m is slope of wear- time curve and t is cutting time.

As an increase in wear is dependent on the given cutting conditions [20], tool wear can be expressed as:

$$w = w_0 + a_0 \cdot V^{a1} \cdot f^{a2} \cdot d^{a3} \cdot t^{a4} \qquad (6)$$

where a_0, a_1, a_2, a_3, a_4 are constants.

If machining time is maintained constant, then tool wear can be said to be function of process parameters i.e. cutting speed, feed and depth of cut i.e. w = f (V, f, d)

A mathematical model for tool wear as a function of process parameters was proposed as:

$$w = a_0{}' \cdot V^{a1'} \cdot f^{a2'} \cdot d^{a3'} \qquad (7)$$

where w is tool wear, V is cutting speed in m/min, f is feed in mm/rev, d is depth of cut in mm, a_0', a1', a2', a3' are constants, which can be found out experimentally.

3. EXPERIMENTAL:

3.1. Material:

For the experimental purpose tool steel Vanadis23 material was procured from Bohler-Uddeholm India Pvt. Ltd. The chemical composition of material given by source Company is as shown in Table 1. (Appendix)

3.2 Cryogenic Treatment:

First 48 Vanadis23 PM steel tool pieces are conventionally heat treated in vacuum furnace. The heat treatment process used is as shown Fig.1 in which the material is subjected to austenitizing at temperature 1040^0C and tempered twice at a temperature of 500^0C and 530^0C respectively. The objective of experiments in this research work is to study the performance and correlate the process parameters in turning and establish an empirical model to evaluate the effect of cryogenic temperature on wear resistance of cryogenically treated Vanadis23 PM steel tool. There are four parameters effect of which is to be studied on tool wear; hence it is decided to use Taguchi OA technique for carrying out experiments. Taguchi L_{16} (2^{15}) array is finalized to be used. As effect of cryogenic temperature is to be studied hence cryogenic temperature is decided to be used at 4 levels. As in case of standard L_{16} (2^{15}) array, columns are required to be merged, if levels of factors are 4 instead of 2. Therefore column number 1, 2 and 3 of standard L_{16} (2^{15}) are merged to create column number 1and cryogenic temperature is allocated to this column. From the remaining three parameters cutting speed, feed and depth of cu it has been observed that cutting speed has the highest effect on tool wear hence four levels of cutting speed are decided to be used. As discussed previously, to accommodate a factor at 4 levels, again column no. 4, 8 and 12 are merged to have column number 2 and cutting speed is allocated to this column. Feed and depth of cut are used at two levels and allocated column number 5 and 6. Remaining columns are kept blank for error. Thus modified L_{16} as shown in Table 2 having two factors at four levels and two factors at two levels is finalized for cryo treated tools experimentations [18].

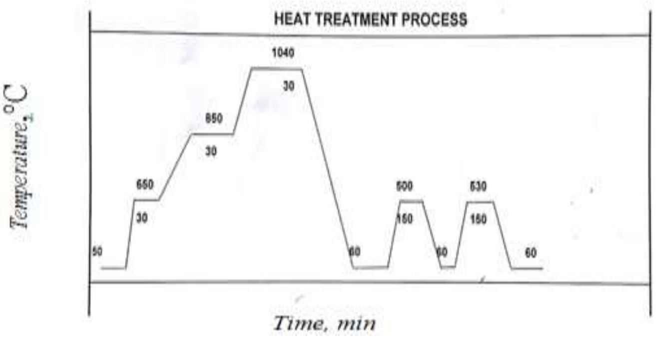

Figure 1: Heat Treatment Process

After heat treatment, 36 pieces are given cryogenic treatment. Three different cryogenic treatments at temperatures: -70°C, -125°C and -190°C respectively followed by four tempering cycles at temperature 150°C, 150°C, 180°C and 525°C respectively are applied to the samples. The soaking time for each cryogenic temperature used is 4 h and tempering period used is 1.5 h for first three tempering and 2 h for fourth tempering. From 36 pieces, each group of 12 samples subjected to cryogenic treatment temperatures at: -70°C, -125°C and -190°C respectively after conventional heat treatment and then to four tempering cycles as mentioned above. Later on all samples ground to single point cutting tools as per standard geometry.

3.3. Testing:

To conduct experiments, heat treatment and cryogenic treatment of tools the process parameters and their values at different levels used are as shown in Table 2 (a) and (b) respectively. (Appendix) Using these tools and mild steel- Fe 410 as work piece material, turning operations are performed on the CNC machine ACE DESIGNERS, APPOLLO. For experimentations, modified L_{16} array repeated for three times maintaining all other factors constant under dry conditions. The experimental results and S/N ratios of tool wear are shown in Table 3 (Appendix). The flank wear measurement of each tool is done by using Mitutoyo make tool maker's microscope.

4. ANALYSIS OF DATA:

By using Taguchi method, followed by ANOVA calculations, it is noticed that the tool wear is different under employed conditions. From Table 4 (Appendix), it is seen that cryogenic temperature, cutting speed and feed these factors have significant effect on wear of the tool. The effect of depth of cut factor is not observed. For the selected parameters for experimentations the analysis indicates that cutting speed, feed and cryogenic temperature are in descending order.

The S/N ratio (dB) and average tool wear for different factor levels is graphically shown in Figures 3.

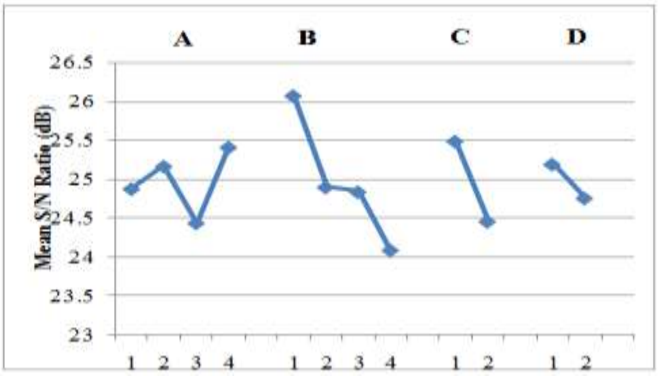

Figure 3: Average S/N Ratio by Factor Level for Tool Wear for Cryo Treated Tools Experimentations

A – Cryogenic treatment temperature, T_c (℃), B – cutting speed (m/min), C- Feed (mm/rev), D – Depth of cut (mm)

By using non linear regression analysis, empirical mathematical model for finding the effect of process parameters on tool wear (response) of cryogenically treated Vanadis23 PM steel tool obtained is given as follows:

$$\ln w = T_c \ln 1.00016 + V \ln 1.033623 + f \ln 3404.633 + d \ln 1.923732 + \ln 0.010218 \qquad (8)$$

where w is tool wear in mm, Tc is cryogenic temperature in °C, V is cutting speed in m/min, f is feed in mm/rev and d is depth of cut in mm. The coefficient of determination, R^2 for developed model is 0.606512.

4.1 Confirmation Experiments:

The response ratio and S/N ratio can be used to determine the optimum condition, which is essentially the optimum combination of the treatment levels for the given response. As the quality characteristic, wear, w is a smaller-the better characteristic, the smallest response is the ideal level for a parameter. The S/N ratio though will be always be highest at the optimum condition, but it is always desired that the signal to be much higher than the noise. Though not all treatment combinations have been run in the experiment, it requires a separate analysis, which considers all possible treatment combinations. From the data obtained in the Table 3 the optimum treatment combination is selected. The optimum combination is A_4, B_1, C_1, D_2 i.e. cryogenic treatment temperature, -190℃, cutting speed, 12 m/min, feed 0.1mm/rev and depth of cut 0.575 mm. This optimum condition has been used for the experimentation. To verify the optimum combination it is necessary to use a predictive equation to predict a response value given in the combinations of each factor at its level in the optimum combination. A simple yet effective equation generally used for such type of study is given by Fowlkes and Creveling [19] as:

$$y_{predicted} = y_{\exp} + \left(\overline{y_A} - y_{\exp}\right) + \left(\overline{y_B} - y_{\exp}\right) + \left(\overline{y_C} - y_{\exp}\right) + \left(\overline{y_D} - y_{\exp}\right) \qquad (9)$$

where $y_{predicted}$ = the predicted response value (in this case wear, w) or S/N ratio: y_{exp} = the overall mean response or S/N ratio of the experimental runs (in this case, wear, w) or S/N ratio: and y_A, y_B, y_C, y_D = the response or S/N ratio for factors A, B, C, and D respectively (these are cryogenic temperature, cutting speed, feed and depth of cut).

Applying the formula (9) to the data in Table 3 a predicted response at the ideal condition is 0.045676 mm and predicted S/N ratio is 26.806198.

Next, the robustness of this parameter optimization was checked experimentally. For this three experiments were conducted at both the optimum condition and one of the other experimental combinations. Then tool wear was measured by using the same arrangement. The results obtained for these confirmation runs, including responses are shown in Table 5 (Appendix), which can be used to interpret robustness of this experiment. The "non optimum" condition was that treatment combination which yielded the highest response in the experimental runs. As observed from Table 5 the error between predicted and confirmation runs results are very low. As well as Table 5 shows the tool wear calculated by using the empirical mathematical model developed, for both conditions according to equation no. (8). The error between actual measured wear and calculated from empirical mathematical model for both the optimum and non optimum condition combination is very less and it indicates validity of the developed empirical mathematical model.

5. RESULTS AND DISCUSSION:

From the analysis it is observed that there is effect of cryogenic temperature on the tool wear. The tool wear reduces as cryogenic treatment temperature reduces. It means wear resistance improves as the cryogenic temperature reduces thus it improves the tool life. This improvement in wear resistance is mainly due to transformation of retained austenite into martensite up to martensitic temperature and afterwards refinement of carbide particles in the microstructure. Figure 4 (a) and (b) show microstructure of conventionally treated and cryogenically treated at -190°C tools obtained by SEM respectively. From these microstructures it is seen that there is reduction in size of carbides and refinement of distribution of carbides in cryogenic treated tools as compared to conventionally treated tools. Because of this the wear resistance of Vanadis23 steel tool has been improved. This is in agreement with the results obtained for tool steels by earlier research [5,6,8,13,21].

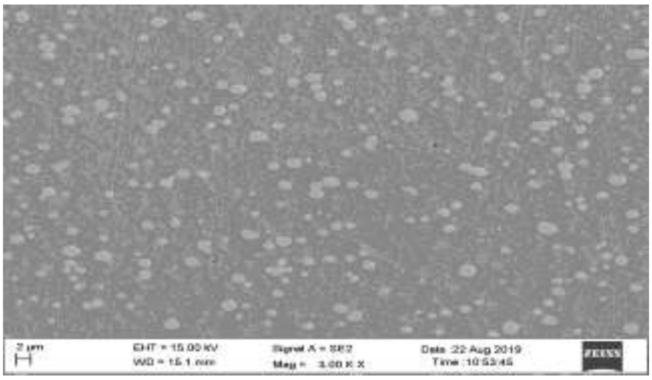

Figure 4 (a): Microstructure of conventionally Treated Vanadis23 PM Specimen

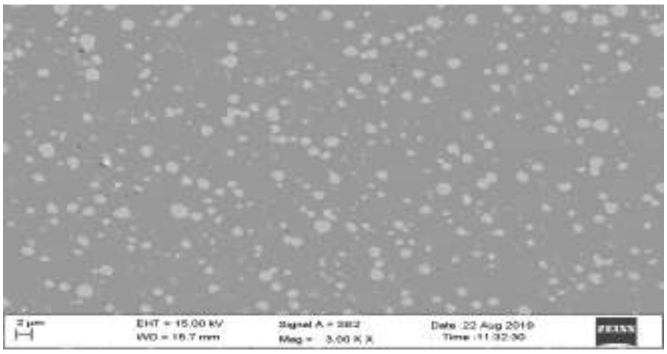

Figure 4 (b): Microstructure of Cryogenically Treated at -190°C Vanadis23 PM Specimen

6. CONCLUSIONS:

- Cryogenically treated Vanadis23 steel tool is used for studying the performance in turning and correlating the turning parameters to establish an empirical mathematical model to obtain tool wear. Taguchi's L_{16} orthogonal array is used for finalizing number of experiments. The model developed can be used to predict tool wear for different combinations of cryogenic temperature, cutting speed, feed and depth of cut in turning operations. The coefficient of determination, R^2 for developed model is 0.606512.
- The results obtained from experimentation are later on confirmed by conducting optimum and one of the non optimum conditions.
- The experimental results, predicted results and results obtained from developed model are in good agreement.

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Appendix

Table 1: Chemical Composition of PM Vanadis23 Tool Steel

C	Si	Mn	P	S	Cr	Mo	W	V
1.30	0.57	0.33	0.022	0.008	4.02	4.85	6.12	3.00

Table 2(a): Process Parameters and Their Values at Different Levels for Conventionally Treated Tools Experimentations

Process parameters	Symbol	Level 1	Level 2	Level 3	Level 4
Cutting speed, m/min	V	12	13.8	15.87	18.25
Feed, mm/rev	F	0.1	0.115	---	---
Depth of cut, mm	d	0.5	0.575	---	---

Table 2(b): Process parameters and Their Values at Different Levels for Cryo Treated Tools Experimentations

Process parameter	Symbol	Levels			
		1	2	3	4
Cryogenic temperature, ˚C	$T_{c,}$	Room temp.	-70	-125	-190
Cutting Speed, m/min	V	12	13.8	15.87	18.25
Feed, mm/rev	f	0.1	0.115	---	---
Depth of Cut, mm	d	0.5	0.575	---	---

Table 3: Experimental Results and S/N Ratios of Tool Wear, w

Exper-iment No.	Column No.				Actual setting values				Results Tool wear, w (mm)			S/N ratio (dB) for tool wear
	1	2	5	6	Tc ˚C	V (m/min)	f (mm/rev)	d (mm)	Set I Y_1	Set II Y_2	Set III Y_3	
1	1	1	1	1	28	12.0	0.100	0.500	0.05	0.046	0.048	26.370152
2	1	2	1	2	28	13.8	0.100	0.575	0.053	0.056	0.058	25.082182
3	1	3	2	1	28	15.87	0.115	0.500	0.058	0.053	0.054	25.186052
4	1	4	2	2	28	18.25	0.115	0.575	0.07	0.068	0.078	22.837740
5	2	1	2	1	-70	12.0	0.115	0.500	0.052	0.047	0.047	26.245193
6	2	2	2	2	-70	13.8	0.115	0.575	0.062	0.057	0.064	24.283300
7	2	3	1	1	-70	15.87	0.100	0.500	0.056	0.059	0.052	25.076587

8	2	4	1	2	-70	18.25	0.100	0.575	0.052	0.051	0.064	25.039472
9	3	1	2	2	-125	12.0	0.115	0.575	0.06	0.063	0.058	24.383819
10	3	2	2	1	-125	13.8	0.115	0.500	0.064	0.062	0.058	24.238891
11	3	3	1	2	-125	15.87	0.100	0.575	0.064	0.063	0.065	23.875694
12	3	4	1	1	-125	18.25	0.100	0.500	0.054	0.049	0.061	25.210489
13	4	1	1	2	-190	12.0	0.100	0.575	0.034	0.042	0.052	27.270759
14	4	2	1	1	-190	13.8	0.100	0.500	0.053	0.048	0.05	25.955654
15	4	3	2	2	-190	15.87	0.115	0.575	0.054	0.058	0.053	25.186052
16	4	4	2	1	-190	18.25	0.115	0.500	0.065	0.071	0.071	23.215727

Table 4: ANOVA and 'F' Test for Tools Flank Wear

Source	SS	DOF	Variance	F ratio	Pure sum of squares	% Contribution
Cryogenic Temperature, T_c	2.129141	3	0.709713	1.021828	0.045483	0.225135
Cutting Speed, V	8.118353	3	2.706117	3.896202	6.034695	29.871075
Feed, f	4.310001	1	4.310001	6.205434	3.615448	17.896069
Depth of cut, d	0.783104	1	0.783104	1.127494	0.088551	0.438317
Error	4.861869	7	0.694552			51.569404
Total		15				100

Table 5: Results of Confirmation Experiments

Confirmation experiment combination	Chosen parametric values				Experimental results wear (mm)				Predicted values		As per developed model	
	T_c	V	f	d	Expt1	Expt2	Expt3	Average	Wear (mm)	% error	Wear (mm)	% error
Optimum	-190	12	0.1	0.575	0.035	0.042	0.049	0.0426	0.0456	6.5789	0.0484	11.983
Non-optimum	28	18.25	0.115	0.575	0.070	0.071	0.075	0.0703	0.0688	2.1337	0.0696	1.0379