Parametric Optimization of Turning Operation using Cryogenically Treated and Un-Treated High Speed Steel Tool

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Abstract

High-speed steel (HSS) tools are the most commonly used tools in small and medium-scale industry. Cryogenic treatment can be used to enhance the tool life. Studies on cryogenically treated (CT) cutting tools show micro structural changes in the material that can influence the life of the tools significantly. This paper primarily reports performance of CT HSS tools as compared to untreated (UT) HSS tools. The results show that CT HSS tools exhibit better performance based on power consumed by lathe machine in turning operation using CT HSS and UT HSS tools. The microstructure has been found more refined and uniformly distributed after cryogenic treatment of HSS tool. Taguchi L_{25} orthogonal array was considered for conducting the experimentation and Analysis of variance (ANOVA) used for data analysis.

Three parameters such as cutting speed, feed rate and depth of cut at different levels were considered in the study. Optimum machining parameters in both the cases (CT HSS and UT HSS tools) are higher cutting speed (75.7 m/min.), higher feed rate (0.35 mm/rev.) and medium depth of cut (0.40 to 0.45 mm). ANOVA results shows that in case of CT HSS tool, feed rate is the most significant parameter followed by cutting speed and in case of UT HSS tool, cutting speed is the most significant parameter followed by the feed rate. It has been observed based on the comparison of total power consumed by the lathe machine that performance of CT HSS tools is better than that of UT HSS tools.

Key words: Cryogenic treatment, high-speed steel tools, nose radius, tool wear.

1. INTRODUCTION

The commonly used cutting tool material in conventional machine tools is high-speed steel (HSS). As the technology has been rapidly advancing, newer cutting tool materials such as cemented carbides, cermets and ceramics are needed to machine many difficult to machine materials at higher cutting speeds and metal removal rates with performance reliability.

In recent years, increased interest in the effects of low temperature on tool and die materials, particularly HSS tools, has been demonstrated. Over the past few years, there has been an increase in the application of cryogenic treatment to different materials. Research has shown that cryogenic treatment increases product life, and in most cases provides additional qualities to the product, such as stress relieving, toughness, etc. In the area of cutting tool, which includes HSS and medium carbon steels, cryogenic treatment can double the service life of tools.

Mohan Lal et al. [1] studied the improvement in wear resistance and the significance of treatment parameters in different tool and die materials. They found that cryogenic treatment imparts nearly 110% improvement in tool life. Cohen et al. [2] proved that the power consumption of cryogenically treated (CT) HSS tools is less when compared to the untreated HSS tools. Cryogenic treatment of tool steels is a proven technology to increase the wear resistance and extend intervals between component replacements for blades, bits, machining mills, etc., and hence improves surface quality of the machined parts. Combining optimized lubrication, correct mechanical configuration and cryogenic treatment of wearing parts results in the maximum performance of lubricated components and can significantly extend the component life. Reliability of operating is influenced by five factors: component design, manufacture, specifications, installation and maintenance.

Each of these stages can be influenced by separate individuals or teams, but ultimately the responsibility for performance of the assembled system falls on the plant maintenance team. It has been said that machines do not die, people kill them. In many cases this is true, and many of the contributing factors

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to premature failure can be controlled by the end user. However, if the equipment has been properly installed and maintained, exerting influence on the other factors may be difficult or impossible for the end user. Cryogenic treatment has been claimed to improve the wear resistance of steels and has been implemented in cutting tools since long. Although it has been confirmed that cryogenic treatment improves the wear resistance and tool life, the process has not been standardized, with the results being inconsistent, varying from researcher to researcher [3].

The literature published in this regards reports that cryogenic treatment facilitates the formation of carbon clustering and increases the carbide density in the subsequent heat treatment, which further improves the surface quality and wear resistance of steels. Cryogenic treatment is a sub-zero thermal treatment generally given to ferrous tool materials. In this treatment, the tool materials are subjected to temperature below −196°C (−320°F) for 20–60 hours in well-insulated chambers and liquid nitrogen (LN_2). Studies on CT HSS tools show micro structural changes in the material that can influence tool lives and productivity significantly [4].

The life of cutting tool is affected by factors like cutting speed, feed and depth of cut, tool material, heat treatment of the tool, work material and nature of cutting. The main characteristics of a good cutting tool material are its hot hardness, wear resistance, impact resistance, abrasion resistance, heat conductivity, strength, etc. What is important to tool life is the likely changes in these characteristics at high temperature because the metal cutting process is always associated with generation of high amount of heat, and hence high temperatures. Cutting speed has the maximum effect on tool life, followed by feed rate and depth of cut. All these factors contribute to the rise of temperature. That is why it is always said that an ideal tool material is the one which will remove the largest volume of work material at all speeds. It is, however, not possible to get a truly ideal tool material. The tool material which can withstand maximum cutting temperature without losing its principal mechanical properties (especially hot hardness) and geometry will ensure maximum tool life, and hence will give the most efficient cutting of metal [5].

During the cutting operation, cutting tool is subjected to static and dynamic forces, high temperatures, wear and abrasion [6]. Singh [7] conducted experimentation on the effect of cryogenic treatment on machining characteristics of titanium alloy (Ti–6A1–4V). In his experimentation, he predicted the best rpm range for conventional milling of titanium alloy (Ti–6A1–4V) using HSS tool material. The specimen was a cryogenic treated cylindrical rod for which a cryogenic treated HSS end mill was used to generate a cavity. The mechanical properties, namely, surface roughness, surface hardness, metal removal rate, and tool wear rate of the machined surface, were observed to find out the best range of machining characteristics. The results indicated that best machining range is between 300 and 500 rpm, surface roughness improves by 47.91%, surface hardness increases by 2.25%, material removal rate increases by 4.38% and the tool wear rate decreases by 52.9%.

Grewal [8] studied the effect of cryogenic treatment of the wire on machining performance of wire cut Electric Discharge Machine. He found in his study that metallic materials having high mechanical strength generally show a low electric conductivity, whereas those having a high electric conductivity generally show a low mechanical strength. With the help of cryogenic treatment of wire, current carrying capacity of the wire can be increased. It is also expected that the cryogenic treated wire would have less chances of breakage during machining as compared to untreated wire because of increase in its toughness.

Vadivel et al. [9] reported that cryogenic treatment has been acknowledged in several researches as a means of extending the tool life of many cutting tools. Studies on CT cutting tools show micro structural changes in the material that can influence the life of the tools significantly. Tungsten carbide cutting tools are now commonly used in the industry. So far, only a few detailed studies have been carried out pertaining to the cryogenic treatment of carbides. This paper primarily reports and analyzes various performances of CT coated carbide inserts and UT coated carbide inserts in turning of nodular cast iron. From the results, it can be seen that CT coated carbide inserts exhibit better performance based on the surface roughness of the work specimen, power consumption, and flank wear than the UT ones. The scanning electron microscope analysis is carried out for the worn out CT and UT coated carbide inserts to predict the wear resistance.

2. EXPERIMENTATION & METHODOLOGY

Turning is a widely used machining process in which a single point cutting tool removes material from the surface of a rotating cylindrical work piece. Three cutting parameters i.e speed, feed rate and depth of cut must be determined in a turning operation. The parameters alongwith their levels & range considered for experimentation has shown in Table 1, 25 experiments were carried out by Taguchi method L_{25} orthogonal array. The experimental design has been done using popular software, specifically used for design of experiment applications, known as MINITAB 15.

TABLE 1 CUTTING PARAMETERS AND THEIR LEVELS (FOR CT AND UT HSS TOOLS)

Level	Cutting speed (m/min) (A)	Feed rate (mm/rev.) (B)	Depth of cut (mm) ©
01	11.3	0.15	0.30
02	20.9	0.20	0.35
03	33.1	0.25	0.40
04	49.9	0.30	0.45
05	75.7	0.35	0.50

Two cutting tool blanks T-42, S-400, 1/2″x 4″ were purchased from Mirinda Tools Pvt. Ltd., one tool was kept un-treated and the other one got cryogenically treated from the Institute for Auto-Parts and Hand Tool Technology (UNDP-UNIDO assisted Punjab Govt. Project), focal point, Ludhiana, Punjab. The tools were prepared as per desired tool geometry. The desired angles and nose radius were cut on profile grinder machine from the R and D centre for Bi-cycle and Sewing Machine, Ludhiana. Brief experimental conditions, machine tool and equipment specifications are given in Table 2.

Turning operation was carried out on the work specimens using cryogenically treated and untreated HSS tools. Various experimental runs using both the cutting tools (CT and UT HSS) were performed by changing the machining parameters at a fixed length of cut. The power consumed by the lathe machine for performing each experimental run was predicted.

TABLE 2 EXPERIMENTAL CONDITIONS, MACHINE TOOL AND EQUIPMENT SPECIFICATIONS

Sr. No.	Parameter/item	Experimental conditions/ M/C tool and equipment specifications
01	Machine tool	High-power rigid lathe machine, 6.5-feet bed, 3-phase 2 HP motor
02	Cutting tools	Untreated Mirinda make, HSS T-42, S-400 (UT) 1/2″x 4″ single point turning tool. Cryogenically treated, HSS T-42, S-400 (CT) 1/2″x 4″ single point turning tool. Chemical composition; C-1.430, Cr-3.920, Mo-3.560, W-8.56, V-2.900, Co-9.45.
03	Tool geometry	Back rake angle: 08°, side rake angle: 10°, end flank angle: 05°, side flank angle: 05°, end cutting edge angle: 15°, side cutting edge angle: 15°, nose radius: 0.5 mm (as recommended by M/S Mirinda Tools Ltd. for machining mild steel)
04	Work material	Mild steel, AISI/SAE-1020, Diameter 36 mm, same for both the tools Chemical composition; C-0.190, S-0.40, P-0.38, Si-0.140, Mn-0.43.

A *Methodology*

- Power consumed by the lathe machine for each experimental run was predicted.
- Microstructure of both the tools (CT and UT HSS) has been obtained using a metallurgical microscope with magnification X100 as shown in Fig. 1.

Fig. 1 Metallurgical microscope

3. RESULTS AND DISCUSSION

The experiments were conducted as per Table 3 using L_{25} orthogonal array. After the completion of experimentation, data was used to calculate signal to noise S/N ratio using Taguchi method. The main objective of the experiment is to optimize machining parameters (cutting speed, feed rate and depth of cut) to achieve low value of power consumption.

TABLE 3 EXPERIMENTAL DESIGN USING L_{25} ORTHOGONAL ARRAY FOR CT AND UT HSS TOOLS

Exp. run	Cutting speed (m/min.)	Feed rate (mm/rev.)	Depth of cut (mm)	Cryogenically treated (CT)		Un-treated (UT)	
				Power consumption (WH)	S/N ratio	Power consumption (WH)	S/N ratio
1	11.3	0.15	0.30	45	-33.0643	50	-33.9794
2	11.3	0.20	0.35	42	-32.4650	48	-33.6248
3	11.3	0.25	0.40	49	-33.8039	46	-33.2552
4	11.3	0.30	0.45	51	-34.1514	52	-34.3201
5	11.3	0.35	0.50	52	-34.3201	52	-34.3201
6	20.9	0.15	0.35	46	-33.2552	47	-33.4420
7	20.9	0.20	0.40	44	-32.8691	46	-33.2552
8	20.9	0.25	0.45	42	-32.4650	51	-34.1514
9	20.9	0.30	0.50	49	-33.8039	52	-34.3201
10	20.9	0.35	0.30	47	-33.4420	55	-34.8073
11	33.1	0.15	0.40	43	-32.6694	48	-33.6248
12	33.1	0.20	0.45	44	-32.8691	49	-33.8039
13	33.1	0.25	0.50	43	-32.6694	47	-33.4420

14	33.1	0.30	0.30	46	-33.2552	48	-33.6248
15	33.1	0.35	0.35	48	-33.6248	47	-33.4420
16	49.9	0.15	0.45	44	-32.8691	50	-33.9794
17	49.9	0.20	0.50	46	-33.2552	52	-34.3201
18	49.9	0.25	0.30	50	-33.9794	48	-33.6248
19	49.9	0.30	0.35	52	-34.3201	49	-33.8039
20	49.9	0.35	0.40	53	-34.4855	51	-34.1514
21	75.7	0.15	0.50	45	-33.0643	50	-33.9794
22	75.7	0.20	0.30	48	-33.6248	52	-34.3201
23	75.7	0.25	0.35	50	-33.9794	54	-34.6479
24	75.7	0.30	0.40	52	-34.3201	54	-34.6479
25	75.7	0.35	0.45	51	-34.1514	53	-34.4855
				Total = 1182		Total = 1251	

TABLE 4 ANALYSIS OF VARIANCE FOR POWER CONSUMPTION (WH), USING ADJUSTED SS FOR CT AND UT HSS TOOL

Source	Degrees of freedom		Sequencial Sum of squared deviation		Adjusted Sum of squared deviation		Adjusted Mean squared deviation		Fisher's f ratio (F)		Probability of significance (P)	
	CT	UT	CT	UT	CT	UT	CT	UT	CT	UT	CT	UT
Cutting speed (m/min.)	4	4	79.440	58.960	79.440	58.960	19.860	14.740	4.49	2.96	0.019	0.065
Feed rate (mm/rev.)	4	4	147.440	27.760	147.440	27.760	36.860	6.940	8.33	1.40	0.002	0.294
Depth of cut (mm)	4	4	9.040	18.560	9.040	18.560	2.260	4.640	0.51	0.93	0.729	0.477
Error	12	12	53.120	59.680	53.120	59.680	4.427	4.973				
Total	24	24	289.040	164.960								

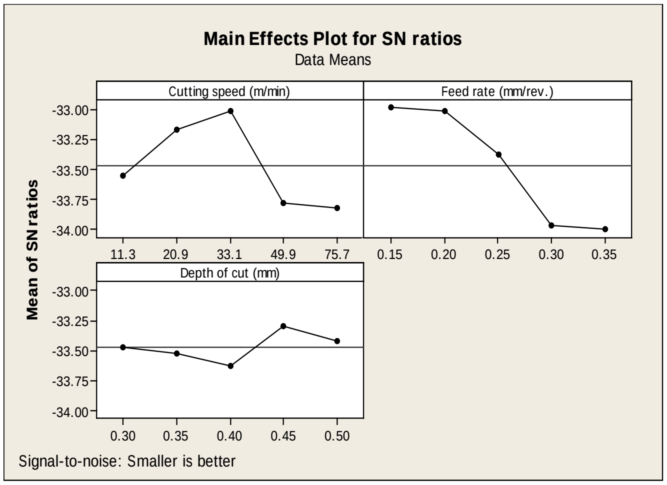

Fig. 2 Main effects plot for signal to noise ratio for CT HSS tool

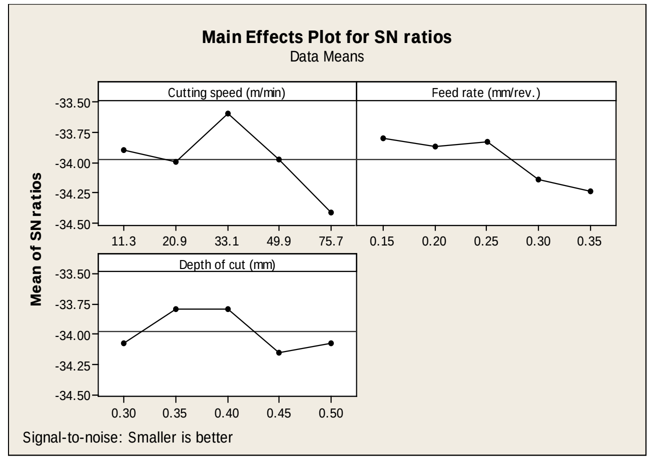

Fig. 3 Main effects plot for signal to noise ratio for UT HSS tool.

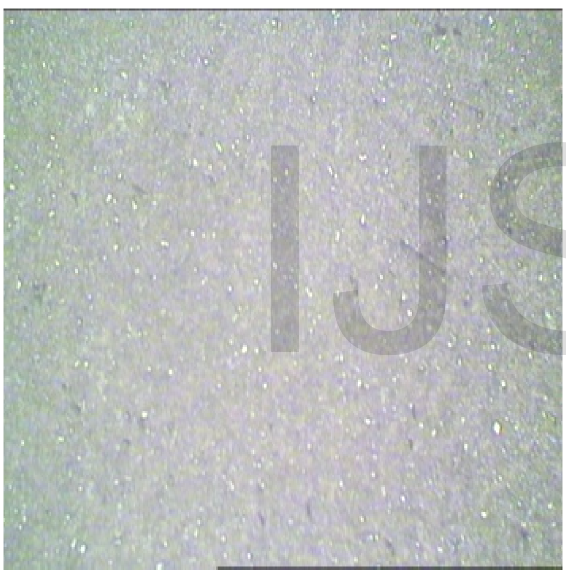

Fig. 4 Microstructure of CT HSS tool material

Fig. 5 Microstructure of UT HSS tool material

So from the S/N ratio characteristics, smaller the better was selected for analysis. The S/N ratio values of the power consumption by lathe machine are calculated, using smaller the better characteristics. The experimental data for power consumption by the lathe machine along with its computed S/N ratio values is given in the Table 3. The plots are developed using a software package MINITAB 15 and the results were further analyzed using ANOVA for the purpose of identifying significant factor, which affects the power consumption. This analysis is carried out for a level of significance of 5% i.e. for a level of confidence of 95%. The F-test is performed to judge the significant parameter affecting power consumption. The larger F-value affects more on the performance characteristics.

From the main effects plots (for both UT HSS and CT HSS, Fig. 2 and 3) for signal to noise ratio, it can be observed that the optimum machining parameters in both the cases are higher cutting speed (75.7 m/min.), higher feed rate (0.35 mm/rev.) and medium depth of cut (0.40 to 0.45 mm). ANOVA results (Table 4) shows that in case of CT HSS tool, feed rate is the most significant parameter followed by cutting speed and in case of UT HSS tool, cutting speed is the most significant parameter followed by the feed rate. The microstructure analysis was carried out to study the microstructure changes in CT HSS and UT HSS tools due to cryogenic treatment. From the microstructure shown in Figures 4 and 5, it can be seen that the microstructure of HSS gets more refined, with uniformly distributed fine alloy carbides in tempered martensite, after the cryogenic treatment.

4. CONCLUSION

The performance of T-42 HSS is quite good because of its composition, especially 10% cobalt. After cryogenic treatment, the performance of cryogenically treated tool had been significantly enhanced. From the analysis of plots for signal to noise (S/N) ratio it has been observed that optimum machining parameters in both the cases (CT HSS and UT HSS tools) are higher cutting speed (75.7 m/min.), higher feed rate (0.35 mm/rev.) and medium depth of cut (0.40 to 0.45 mm). The ANOVA results shows that in case of CT HSS tool, feed rate is the most significant parameter followed by cutting speed and in case of UT HSS tool, cutting speed is the most significant parameter followed by the feed rate. On the comparison based on total power consumption, it has been found that the performance of CT HSS tools is better than that of UT HSS tools. It has also been found that the microstructure of HSS gets more refined and the particles are uniformly distributed with fine alloy carbides in tempered martensite after the cryogenic treatment. Less power consumption, more uniform distribution of metal particles, refined microstructure of CT HSS tool represent the positive scope of cryogenic treatment on tool and die materials.

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