INVESTIGATION OF MACHINABILITY CHARACTERISTICS ON C45 STEEL WITH CRYOGENICALLY TREATED HSS TOOL FOR CUTTING FORCE AND TEMPERATURE USING STATISTICAL TECHNIQUE

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Abstract: In this study, the effect of cryogenic treatment and machining parameters on cutting force and temperature was investigated in the dry turning of C45 steel with treated and untreated M2 HSS tool with the radial nose of 0.4mm, are optimized by using the statistical method. Pilot experiments was carried out in three different speeds (38.6, 57.5, 62.8 m/min) by three different depths of cut (0.2, 0.4, 0.6 mm) and feed rates (0.046, 0.062, 0.087 mm/rev). Experiments were carried out based on L_{27} orthogonal array (3^3) three levels and three factors, analysis of variance (ANOVA) and S/N Ratio is employed to determine the most significant factor in each response. The result shows that the depth of cut is the most significant factor for both treated and untreated tool on cutting force, temperature followed by cutting speed and feed rate has less significance, from statistical method to obtain considerably reduced the cutting force of HSS tool by 9.11% and temperature by 11.5%, while depth of cut was the dominating factor for both

Key words: Deep Cryogenic Treatment, M2 HSS Tool, Cutting force, Temperature, Machining.

1. INTRODUCTION

In the concept of dry machining, there is no scope for contamination, disposal, and filtration due to cutting fluids, [1]; but operate at lower cutting speeds resulting in slow production rate. The possibility of overheating the tool and lack of chip removal mechanisms pose a significant challenge on the scope of dry machining, [2]. In the metal cutting process, cutting tool overcomes the shear strength of work piece and cuts the metal. Advanced manufacturing has produced materials with good strength whose machining demands a paradigm shifts in the cutting tools. These cutting tools need to apply more force to cut while compromising their tool life. High temperature generated during cutting impacts in multiple ways on tool life by causing thermal distortion and dimensional changes thereby affecting accuracy, [3].

The force components that come into play, impacting on the cutting tool during machining process is termed as cutting forces, [4]. They indicate the work done by the tool in removing metal; there by giving an account of tool life, the machined work piece's dimensional accuracy and quality of finished product. High speed steels first produced in the 1900s are the best choice for cutting tools owing to its high toughness and excellent wear resistance characteristics [5]. Its peculiar behaviour of maintaining hardness at elevated temperatures makes it suitable for drilling, cutting, and various machining processes. Molybdenum type HSS are most favoured due to their cost- effectiveness and high abrasion resistance as compared to Tungsten type [6].

A typical interaction between cutting tool with the work piece in machining process is pictured in fig.1. The tool dynamometer measures the cutting forces F_x, F_y, and F_z; and the obtained values can be stored in the computer by Data Acquisition system. F_x describes feed force acting in horizontal plane parallel to the work piece axis. It is also known as thrust force and is responsible for dimensional inaccuracy and vibration. F_y is the primary component (power component) representing cutting force acting in the vertical plane and is tangential to work surface. F_z represents radial feed force acting in the horizontal plane but along the radius of the work piece. F_y and F_z are most and least influential forces respectively. These cutting forces are susceptible even to a small change in the cutting process.

Machinability refers to the ease with which metal can be machined with the desired finishing and is estimated by the length of cutting-tool life.

In machining operations, cutting conditions such as tool signature and process parameters are usually selected to give an economical tool life. In machining operations, cutting conditions such as tool signature and process parameters are usually selected to give an economical tool life.

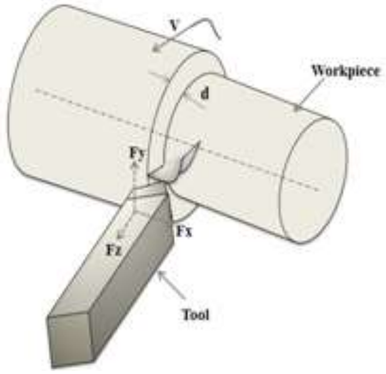


Fig. 1. Illustration of direction of the measured forces during turning

Fig. 2. A typical representation of cryogenic treatment process

During machining, it is observed that cutting forces are directly dependent on the tool geometry and process parameters. If V is cutting velocity, T is tool life, f is feed rate, d is depth of cut, then the relation between tool life and cutting condition according to modified Taylor's equation, is expressed as: $VT^nf^ad^b = K_t$, where K_t is constant, a & b to be determined experimentally for each run.

Heat and friction are prime causes of cutting tool breakdown [9]. A reduction in temperature by 50^0 F results in five folds' improvement in tool life [10]. In machining, heat is generated at three zones: primary shear zone, chip-tool interface and the tool-work piece interface. The primary shear zone temperature affects the mechanical properties of the work piece-chip material and temperatures at tool-chip and tool-work piece interface Influences tool wear at tool face and flank respectively. The energy consumption (or heat generated) in the machining process Pm can be expressed as below:

$$P_m = F_c + V \quad (1)$$

$$P_m = P_s + P_f \quad (2)$$

$$P_f = F_f + V_0 \quad (3)$$

$$P_m = Q_c + Q_w + Q_t \quad (4)$$

where: F_C is cutting force, P_s and P_f are heat generated in primary and secondary shear zone respectively, V_0 is velocity of chip flow, Ff is friction force, and Q_c, Q_w, Q_t represents rate of heat transportation/conduction in chip, work piece and tool respectively.

While chips act as heat sink to dispose a significant amount of heat generated, the remaining small part is spread over tool and work piece. All the heat transfer is via conduction (no material flow) hence no heating within the element. Heat generated during the cutting is distributed among chip, work piece and tool as described in equation (4).

A typical Cryogenic treatment setup is shown in fig.2. A microcontroller-based control system is designed to control the flow of liquid nitrogen into the cooling chamber. The cutting tools are placed in the chamber where the atomized nozzles will spray the liquid nitrogen for direct cooling.

Treating metals and materials under extreme temperature conditions to have morphological changes is an ancient art. In pursuit of enhancing the stability of a work piece/tool, many efforts have been carried out by treating them to extremely high temperatures and/or shallow temperatures. The process of transforming unstable phases into a stable at room temperature by operating the metal at a cold temperature of -120 ^{0}F and beyond is termed as Cryogenic Treatment (CT). It refers to deep and slow cooling of the metal in a controlled bath of liquid nitrogen (LN2). This CT enhances durability, improves wear resistance, and decreases residual stresses while increasing the toughness and dimensional stability.

The CT has a profound effect on resistance to impact by creating more uniform grain structure. It finds its applications in Aerospace and defence, medical and automotive, sports and music, forming and cutting tools, etc, [12]. Cutting tools can be cryogenically treated in two methods: Deep Cryogenic Treatment (DCT) refers to treating heated cutting tool to the cold temperature of up to -196^{0}C whereas Shallow Cryogenic Treatment (SCT) refers to a different cooling temperature of about -110^{0}C, [13].

Recently a cryogenic machining method has surfaced in the field of CT research Scott. Instead of cooling tools separately, a jet of liquid nitrogen is sprayed at the interface of the cutting tool, [14].

Though it is useful in machining operation (especially for rough machining), still it is in limited to research labs and the widespread acceptance of this method is hindered due to the health hazards caused by direct exposure to LN2.

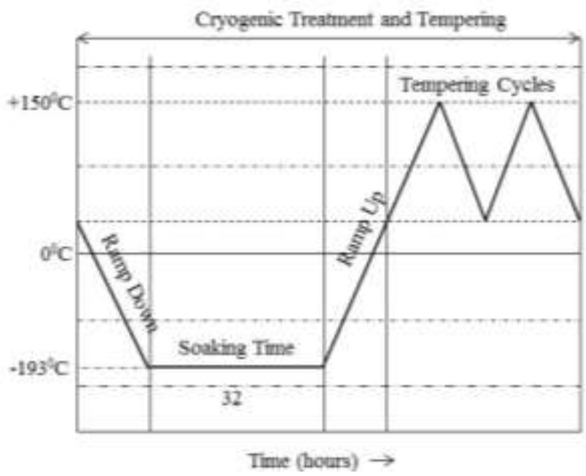


Fig. 3. Deep Cryogenic treatment cycle with double tempering

While treating refers to a process of applying distinct time/temperature profile to modify the performance of materials, tempering relates to a method of heating a tool (instead of cooling) and cools it in air. One can have multiple cycles of tempering based on the required hardness. The tempering temperature is selected based on the alloy composition and the requirements of the finished product, [15].

Figure 3, shows the cryogenic treatment cycle, where the first stage called cooling is done by reducing room temperature to -196^{0}C at the rate of 20c per minute. The second stage called soaking (or holding period) is carried for few hrs (not more than 35 hrs) followed by heating to achieve the ambient temperature. Further, tempering can be done for removal of excess hardness.

2. MATERIALS AND METHODS

Here in this work, we have considered AISI M2 HSS tool for dry machining, turning operation of hot-rolled C45 steel. The treated material has undergone deep cryogenic treatment followed by double tempering. The turning operation was performed using panther 1350/1 center lathe machine equipped with maximum spindle rotation of 1250rpm and 7.5kW drive motor. The cutting operation was conducted at three different cutting speeds (384, 572 and 625rpm), three different feed rates (0.046, 0.062, 0.087mm/rev) and three different depth of cuts (0.2, 0.4, 0.6mm). The chemical composition of AISI M2 HSS tool used for this work is shown in table 2. The angles of cut described in table 1, vary according to various factors. Miranda tool booklet was taken as reference for selecting them.

Table 1. Experimental conditions

Machine tool:	Lathe Machine, 4 hp
Work Specimen	
Material:	Hot rolled C45 steel
Cutting tool:	M2 HSS
Tool holder:	Kistler
Tool Signature	
Back rake angle:	6^0
Side rake angle:	6^0
End relief angle:	6^0
End cutting edge angle:	30^0
Side cutting edge angle:	15^0
Nose radius:	0.4mm
Process Parameters	
Cutting velocity:	38.6, 57.5 & 62.8 (in m/min)
Feed rate:	0.046; 0.062 & 0.087 (in mm/rev)
Depth of Cut:	0.2; 0.4 & 0.6 (in mm)
Environment:	Dry machining

Table 2. Chemical composition of AISI M2 HSS tool

Element	C	W	Mo	Cr	V
Wt.(%)	0.86	6.0	4.90	4.0	1.90

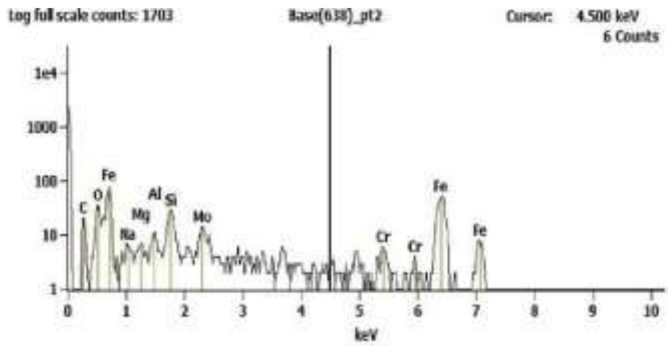


Fig. 4. Electronic dispersive Spectrography of deep cryotreated tool

Table 3. Experimental data during hardness test

Type of Sample	Hardness (HRc) Top	Middle	Bottom	Mean
Untreated	52	55	54	53.6
Cryotreated	60	63	62	61.6

An Electron Discharge Spectrography (EDS) through X-rays was conducted on the top surface of both treated and untreated tool for chemical composition. The images are evident for few morphological changes that have occurred due to cryogenic treatment. The EDS image of the treated tool is shown in figure 4.

Hardness was measured on the R_c scale using Rockwell hardness machine. Sandpaper was used to prepare a surface of the tool. To settle the specimen a minor load of 10 kg was applied, later replaced by 150kgs of the major load for about 15 sec. A dial gauge was used to record the resistance to indentation automatically. An average of total six readings for both samples (treated and untreated) was documented as shown in table 3.

Cryotreatment plays a vital role in developing steel tribological properties, [16]. There have been few efforts in optimizing the CT parameters. Based on the analysis of various heat treatment parameters, DC conditions are decided. The overwhelming popularity of steel and the success rate of DCT enforce us to explore the optimization techniques, [17]. Traditionally the optimization is done on the trail-and-error basis depending on the manufacturer’s data sheet and design engineer’s specifications. Since these details pertain to general steel, might not be suitable for treated one, also it is cumbersome to optimize when the number of process parameters raise.

In the given scenario, Taguchi Design of Experiments (DOE) stands out as the best candidate for critical parameter optimization of given process. It is a statistical method, where optimization is achieved by decreasing the variation in time. The independent/ simultaneous evaluation of two or more variables is possible by Taguchi's orthogonal series. The difference between experimental value and the desired value is converted into a loss function, which is used in the calculation of standard deviation. This loss function turns data into S/N ratio. Thus, largest SNR represents the best performance, [18]. There are three categories of S/N ratio performance: nominal is best (such as loss, as nominal as possible), smaller is the better (such as wear, as lower as possible), and higher is the better (such as material removal rate, as large as possible). In the current study, S/N ratio is calculated with an approach of "smaller is the better", [19].

$$[S/N]_{SB} = -10\log\left(1/n\sum_{-=n}^{n} {}_{i}^{2}Y\right) \qquad (5)$$

Where y_i is the observed data at i^{th} experiment and n is number of experiments.

2.1 Design of experiment

In the turning process, the impact of DCT and machining parameters on the cutting force and machining temperature were investigated using Taguchi optimization technique. The Taguchi L_{27} (3^3 standards 3 level orthogonal array) possessing 26 degree of freedom (DOF) was chosen in this study. Thus, each picked parameter was probed at three levels. The S/N ratios (estimated according to the smaller is, the better) of Fc and T_m w.r.t. all factors and levels are observed. Table 5 shows the optimal levels of the mean of S/N ratios.

3. THEORY AND CALCULATIONS

Table 3 shows the HRC of M2 HSS tool for both untreated and treated assessed by Rockwell Hardness Tester. Hardness is not an elementary property of a material and must be defined by tests. There is no standard table for hardness and must be measured in a specific manner through a specified indenter shape.

The variations of cutting force in both treated and untreated M2 HSS tools at a feed rate of 0.046, 0.062 and 0.087 mm/rev with cutting speeds of 384, 572, 625rpm for a depth of cut of 0.2, 0.4 and 0.6mm respectively. During the experiment, at all combination of cutting conditions, the deep treated tool exhibited performance better than the untreated concerning cutting force.

The first nine experiments were conducted, keeping the depth of cut constant at 0.2 mm. At a speed of 384 rpm and feed rates of 0.046, 0.062 and 0.087mm/rev; an undesired increase of about 15.93%, 15.97% and 11.79% in cutting force were observed respectively. Alternatively, at a speed of 572 rpm and feed rates of 0.046, 0.062 and 0.087 mm/rev; desired reduction of 13.30%, 17.10% and 26.19% in cutting force were observed respectively. Again, an undesired improvement of 15.16%, 12.86% and 11.83% was noted when all three feed rates were applied at the speed of 625rpm respectively.

The second set of experiments was carried out by changing the depth rate to 0.4mm. The highest improvement (desired reduction in cutting force) was noted to be 17.65% at a higher speed, while only 5.3% was reported at medium speed. A similar change of percentage in cutting force was observed (in the third set) with a maximum improvement (desired reduction in cutting force) of about 29.4% at a lower speed and 6.17% at a higher speed at a depth of cut of 0.6mm.

In the current investigation, Taguchi method was employed for the optimization of each output response. The response table for S/N ratio and main effects plots for S/N ratios of every individual response was shown in Fig 6 to obtain most influencing machining parameter and the optimal parametric setting, respectively. In S/N ratio, Signal is the desired value while noise is the undesired one.

Table 4. Result of quality characteristics and S/N ratio; UT: Untreated, CT: Cryo-treated, T: Temperature, SNR: Signal to Noise ratio

a_p (mm)	Vc (m/min)	f (mm/rev)	F_c (N), UT	F_c, (N) CT	T ^{0}C, UT	T ^{0}C, CT	SNR, F_c, UT	SNR, F_c, CT	SNR, T^{0}C,UT	SNR, T^{0}C, CT
0.2	38.6	0.046	67.5	80.3	62	52	-36.59	-38.10	-35.85	-34.32
0.2	38.6	0.062	72.9	86.8	65	55	-37.26	-38.77	-36.26	-34.81
0.2	38.6	0.087	78.9	89.5	69	59	-37.95	-39.04	-36.78	-35.42
0.2	57.5	0.046	95.5	84.3	72	62	-39.60	-38.52	-37.15	-35.85
0.2	57.5	0.062	104.6	89.3	75	65	-40.39	-39.02	-37.70	-36.26
0.2	57.5	0.087	115.5	91.6	79	69	-41.29	-39.23	-37.95	-36.78
0.2	62.8	0.046	90.5	106.6	83	62	-39.13	-40.56	-38.38	-35.85
0.2	62.8	0.062	96.3	110.5	82	65	-39.67	-40.86	-38.28	-36.26
0.2	62.8	0.087	100.3	113.8	89	70	-40.03	-41.12	-38.99	-36.90
0.4	38.6	0.046	113.6	102.5	85	75	-41.11	-40.22	-38.59	-37.50
0.4	38.6	0.062	118.0	106.0	87	77	-41.44	-40.51	-38.79	-37.73
0.4	38.6	0.087	125.7	110.8	84	80	-41.98	-40.89	-38.08	-38.06
0.4	57.5	0.046	132.1	119.3	87	77	-42.42	-41.54	-38.46	-37.73
0.4	57.5	0.062	130.9	124.3	90	83	-42.34	-41.89	-38.82	-38.38
0.4	57.5	0.087	138.8	130.5	94	87	-42.85	-42.37	-38.79	-38.79
0.4	62.8	0.046	173.5	148.8	90	85	-44.79	-43.45	-39.08	-38.59
0.4	62.8	0.062	178.7	154.9	94	89	-45.04	-43.80	-39.46	-38.99
0.4	62.8	0.087	185.5	157.6	98	91	-45.36	-43.95	-39.82	-39.18
0.6	38.6	0.046	207.1	160.0	87	87	-46.32	-44.08	-38.79	-38.79
0.6	38.6	0.062	210.4	163.4	91	92	-46.46	-44.26	-39.18	-39.28
0.6	38.6	0.087	212.4	165.8	95	94	-46.54	-44.39	-39.55	-39.46
0.6	57.5	0.046	199.4	167.8	93	87	-45.99	-44.50	-39.37	-38.79
0.6	57.5	0.062	201.3	169.3	95	90	-46.08	-44.57	-39.55	-39.08
0.6	57.5	0.087	210.4	175.6	98	91	-46.46	-44.87	-39.82	-39.18
0.6	62.8	0.046	190.3	179.3	95	94	-45.59	-45.07	-39.55	-39.46
0.6	62.8	0.062	195.6	183.5	102	97	-45.83	-45.27	-40.17	-39.74
0.6	62.8	0.087	206.4	189.3	107	91	-46.30	-45.54	-40.59	-39.18

Table 5. Results of S/N ratio for temperature and cutting force

Levels	V_c (m/min)	f (mm/rev)	a_p (mm)	Vc (m/min)	f (mm/rev)	a_p (mm)
Cutting force Untreated				Temperature Untreated		
1	-41.74	-42.39	-39.1	-38.03	-38.39	-37.46
2	-43.04	-42.72	-43.04	-38.74	-38.7	-39.06
3	-43.53	-43.19	-46.17	-39.37	-39.05	-39.62
Max-Min	1.79	0.8	7.07	1.34	0.66	2.16
Cutting force Treated				Temperature Treated		
1	-41.14	-41.78	-39.47	-37.26	-37.43	-35.83
2	-41.83	-42.11	-42.06	-37.87	-37.83	-38.33
3	-43.29	-42.37	-44.73	-38.24	-38.10	-39.22
Max-Min	2.15	0.59	5.26	0.98	0.67	3.39

Table 6. Analysis of variance (ANOVA) results for temperature and cutting force

Source	DOF	Adj. SS	Adj.MS	F-value	P %	Adj. SS	Adj.MS	F-value	P %
Cutting force Untreated						Temperature Untreated			
V_c	2	2485.0	1242.5	182.08	3.80	734.74	367.37	94.47	23.32

f	2	618.4	309.2	45.31	0.95	193.85	96.93	24.92	6.15
a_p	2	56881.8	28440.9	4167.92	87.04	2058.3	1029.15	264.64	65.32
a_p x v_c	4	5265.9	1316.5	192.93	8.06	101.26	25.31	6.51	3.21
a_p x f	4	16.3	4.1	0.60	0.02	16.15	4.04	1.04	0.51
Error	12	81.9	6.8	--	0.13	46.67	3.89	--	1.48
Total	26	65349.4	--	--	100	3150.96	--	--	100
Cutting force Treated						Temperature Treated			
V_c	2	4531.7	2265.8	1927.25	13.72	296.96	148.48	45.04	6.29
f	2	316.2	158.1	134.49	0.96	147.63	73.81	22.39	3.13
a_p	2	2750.8	13754.4	11699.02	83.27	480.07	2040.04	618.89	86.46
a_p x v_c	4	657.2	164.3	139.75	1.99	125.48	31.37	9.52	2.66
a_p x f	4	6.7	1.7	1.43	0.02	29.48	7.37	2.24	0.62
Error	12	14.1	1.2	--	0.04	39.65	3.30	--	0.84
Total	26	33034.8	--	--	100	4719.19	--	--	100

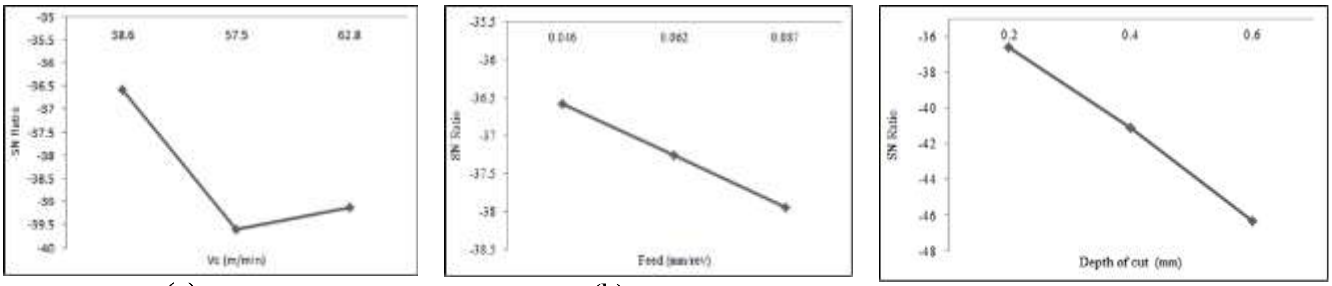
Thus, the most significant (highest) S/N ratio represents optimized value. The average S/N ratio of cutting speed (treated and untreated) and temperature (treated and untreated) values from experimental studies were calculated as -42.1, -42.8; and -37.8, -38.7 respectively. It can be observed from table 5 that depth of cut is the most affecting variable on Cutting force, while the feed rate being the least. The optimal combination of process variables is obtained from the main effects plots for S/N ratios by selecting the highest values. Thus, the optimal combination of process variables is observed as follows; cutting speed at 384rpm, the feed rate at 0.046mm/rev and depth of cut at 0.2mm (for both treated and untreated cutting tools). Results of quality characteristics and S/N ratio are portrayed in table 4.

ANOVA aids us in investigating the significance of the impact of experimental design parameters. Analysis of Variance results for cutting force, P is greater than F is less than 0.05, the control factors and their interactions are significant. The effect of cutting speed, feed rate and depth of cut on cutting force and temperature has been determined by applying ANOVA with 95% reliability. In the current study, the most effective parameter on cutting force is depth of cut with percentage contribution of 87.04% and 83.27% for untreated and treated cutting force respectively.

Similarly, depth of cut was the dominating factor in temperature generation with a contribution of 65.32% and 86.46% untreated and treated respectively. Similar investigations for temperature generated were carried out and a response table for S/N ratio and main effects plots for S/N ratios of every individual response was shown to obtain most influencing machining parameter and the optimal parametric setting, respectively. Here depth of cut seems to be the most dominating variable while feed rate being the least. The optimal condition of process variables was obtained as: cutting speed at 384rpm, the feed rate at 0.046mm/rev and depth of cut at 0.2mm for both untreated and treated condition.

4. RESULTS AND DISCUSSION

A comparative study of the results obtained using both the cutting tools was carried out to show the better ability and adaptableness of cryotreated cutting tools in various manufacturing applications. From the experiments, cutting force depends on cutting speed, feed rate and the depth of cut. In overall, higher depth of cut results in significant increase in cutting force. The surface supremacy of a machined part mainly, affected by the solidity of the nose of the cutting tools.



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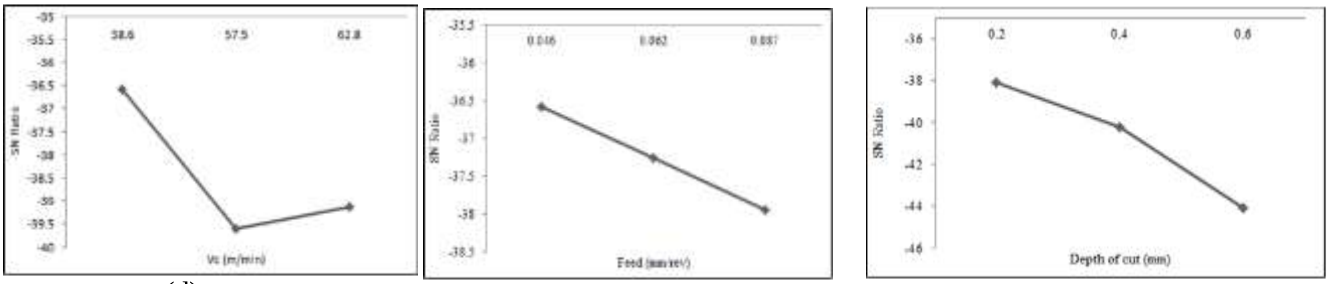
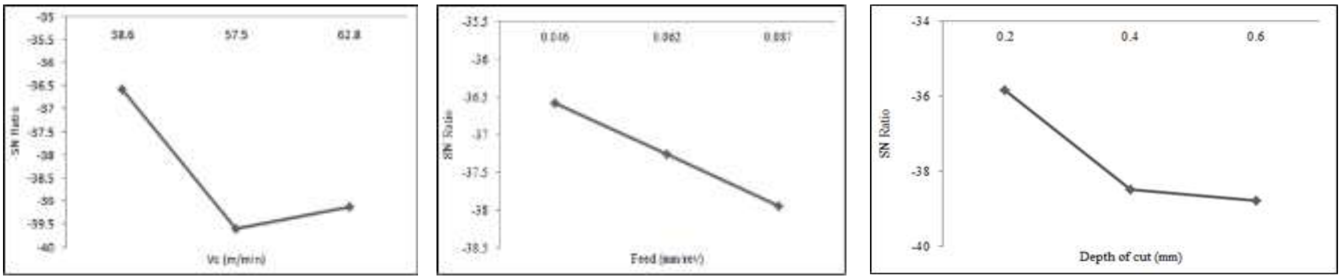
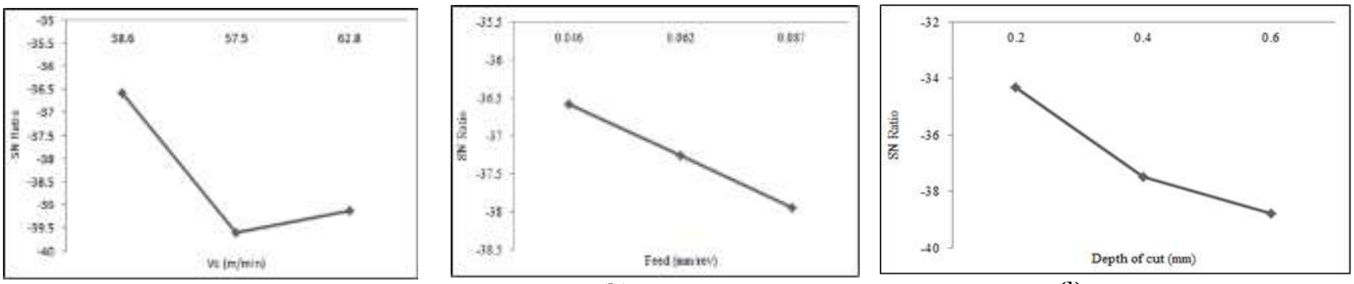


(d) (e) (f)



(g) (h) (i)



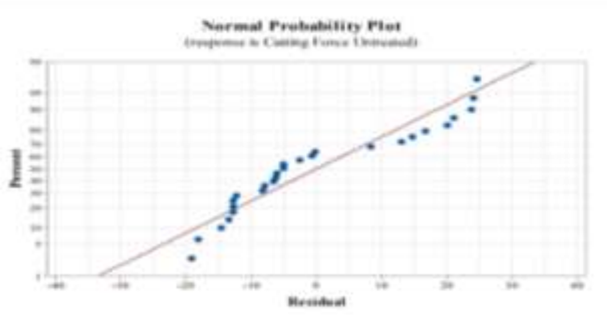
(j) (k) (l)

Fig. 6. Individual results of control factors on the Temperature and Cutting Force, For untreated S/N ratios of cutting force Vs (a) speed (b) feed (c) depth of cut; For treated S/N ratios of cutting force Vs (d) speed (e) feed (f) depth of cut; For untreated S/N ratios of Temperature Vs (g) speed (h) feed (i) depth of cut; and for treated S/N ratios of Temperature Vs (j) speed (k) feed (l) depth of cut. The highest S/N ratio corresponding to optimal conditions are shown. This optimum condition represents the lowest levels of temperature and cutting force values for the control factors: Feed, Cutting speed, and Depth of cut.

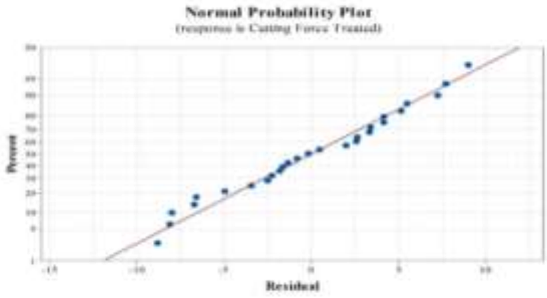
A perfect tool in machining has the capability of replicating its nose fit on the work surface, the lesser cutting force indicates low vibration in turnings and hence lower cutting force is attained on the C45 steel work piece with the cryotreated tools as opposed to untreated ones. It can be observed from the figure that the cutting force and temperature generated is reduced by 9.11% and 11.53% when a cryotreated tool replaces the untreated one.

Normality plots were also used to check whether regression model matches the observed values or to check. Figure 7, the normal probability plot of the residuals for the cutting force and temperature generation seems to follow a straight line which indicates that the error is distributed normally and support to the model to be worthy.

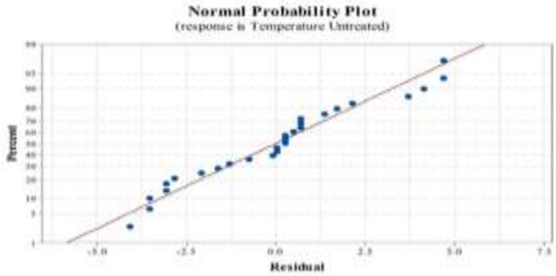
(a)



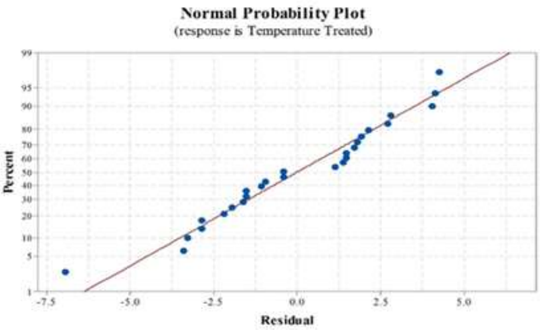
(b)



(c) (d)



(e) (f)



(g) (h)

Fig. 7. Normal probability plot for the residuals and observation order for Cutting Force and Temperature, for untreated cutting force (a & b); for treated cutting force (c & d); for untreated Temperature (e & f); and for treated Temperature (g & h).

5. CONCLUSIONS

Cutting force and Temperature generated are the two vital parameters in deciding the tool life. Though the general literature says that cryo-treatment brings in morphological changes, there are no specific investigations in analyzing the impact of deep cryo-treatment on the cutting force and temperature of a cutting tool used for dry machining. This study focuses on the advent of cryogenic treatment and tempering on cutting force and temperature of M2 HSS cutting tool used in machining of C45 steel. We found an improvement of 9.11% in cutting force, whereas growth in temperature gain was noted to be 11.53% which gradually increase with increasing cutting speed. In this study, the Taguchi technique is used to obtain optimal machining parameters in the cutting of C45steel under the dry conditions. The experimental results were evaluated using ANOVA. The following main conclusion may be drawn on behalf of this study;

- Cryotreatment profoundly improves the cutting force and temperature, which can be attributed to the transformation of soft retained austenite into harder martensite along with the formation of fine carbide particles in the tool.
- At all combination of cutting conditions, deep cryo treated tool performed exceptionally well while being consistent as compared to its untreated counterpart. A low-temperature tempering was found beneficial as it implied positive effects on cutting force and temperature generation.
- Because of pilot trials, it was found that depth of cut is

the dominating factor affecting both cutting force and the temperature generation at the interface of tool and work piece.

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