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Comparative Analysis for Hard Turning of Cryogenically Treated and Non Treated EN8 Steel by Using TNMG 160408 Insert

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Abstract — *En8 steel is the most commonly used steel in applications like gears, bolts, pins, studs, etc. These applications of En8 material require it to be readily machinable and, at the same time, possess a sufficiently high amount of hardness and strength. A conventional heat treatment process used to enhance the mechanical properties of En8 steel consists of quenching and tempering. Cryogenic processing consists of quenching the material, then treating it at a temperature as low as –193°C, followed by material tempering. Turning is becoming more popular for hardened steels as it has several benefits over grinding. The hard-turning process is defined as machining the work material having a hardness greater than 45 H.R.C. PCBN or hardened inserts are dominant tool materials for hard turning applications due to their high hardness, high wear resistance, and high thermal stability. Compared to grinding operations, hard turning has higher material removal rates, the possibility of greater process flexibility and lower energy consumption. The objective of the present work is to compare the results obtained by cyo-treated and non treated workpiece and to establish a correlation between cutting parameters such as cutting speed, feed rate and depth of cut with machining force, material removal rate and surface roughness on both cryo-treated and non treated EN8 workpieces. The TNMG inserts with a chamfer edge profile are used for turning. It is found that the use of lower feed value, lower Depth of cut with the cutting speed 135 and 180 m/min ensures minimum cutting forces, surface roughness and high M.R.R. 235m/min, 0.2 mm/rev, and 0.5 mm is the optimum parameter obtained by Grey Relational Analysis.*

Keywords — *EN8 Steel, Cryogenic treatment, Material Removal Rate (M.R.R.), Force Measurement, Surface Roughness, Response Surface Methodology (R.S.M.), Grey Relational Analysis. (G.R.A.)*

I. INTRODUCTION

A. Turning

Machinability is defined as the ease of machining a material, characterized by low cutting forces, high material removal rate, good surface finish, accurate and consistent workpiece geometrical characteristics, low tool wear rate and good curl or chip breakdown chips etc.

B. Hard Turning

Hard turning is performed on materials with hardness within 45–68 Rockwell range using various tipped or solid cutting inserts, preferably hardened coated inserts, CBN or PCBN. The hard turning process differs from conventional turning because of the workpiece hardness, the required cutting tool, and the mechanisms involved during chip formation. [1,7]

C. Induction Hardening

The hardening process hardens the steel, and tempering increases the toughness. The conventional hardening and tempering processes are carried out on the specimens. The hardening process consists of heating the specimen to austenitizing temperature, typically within the range of 815 to 870 °C, followed by oil quenching.

D. Cryogenic Treatment

Cryogenic material processing is only done after hardening of the material, and post cryogenic treatment tempering is mandatory. In this study, the process followed is austenitizing to 850°C, followed by oil quenching until room temperature is reached; after oil quenching, the material is brought down to a temperature of -193°C with the ramp down rate of 0.5°C/min. Once the cryogenic temperature was achieved, the specimen is held at that temperature with a holding time of 24 hours. After that, the material is brought to room temperature with a ramp-up rate of 0.5°C/min. Double tempering was performed post cryogenic treatment at 150°C for 1 hour. [29]

II. EXPERIMENTAL DESIGN AND SETUP

A. Response surface design

Response surface methods are used to examine the relationship between one or more response variables and a set of quantitative experimental variables or factors.

Response surface methods may be employed to

1. Find factor settings (operating conditions) that produce the "best" response.

2. Find factor settings that satisfy operating or process specifications.

3. Identify new operating conditions that produce improved product quality over the quality achieved by current conditions.

4. Model a relationship between the quantitative factors and the response. [20]

B. Central Composite Designs

Central Composite Design (C.C.D.) has three different design points: edge points as in two-level designs (±1), star points at $\pm\alpha$; $|\alpha| \geq 1$ that take care of quadratic effects and center points, three variants exist circumscribed (CCC), inscribed (CCI) and face-centered (C.C.F.).

Experiments are carried out by using face-centered design. [20]

C. Number of Factors Levels and Factor Levels Values

Table 1: Input Parameter Levels and coding for the machining process.

Factor / ***Level***	Speed (v) m/min	Feed (f) mm/rev	Doc (d) mm	Coding
High	235	0.2	0.5	+1
Medium	180	0.1	0.3	0
Low	135	0.05	0.2	-1

Experiments have been carried out on non-cryogenic treated workpieces and cryogenic treated workpieces by using Central composite design. Total 40 experiments are performed for non-cryo treated and cryo-treated workpieces with 2 sets of 20 combinations designed for each of the output factors, i.e., M.R.R., Fx, Fy, Fz and surface roughness.

Fig.1.1 TNMG 160408 TT5100 Inserts

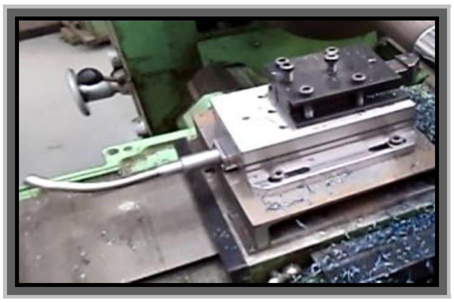


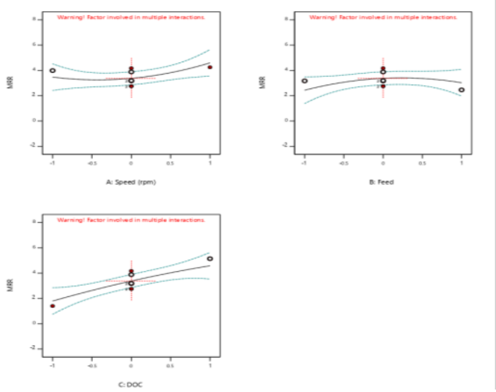
Fig.1.2 Fixture for Dynamometer

Fig.1.3 Turned Workpieces

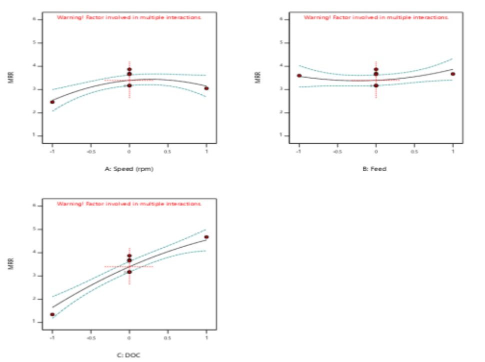
III. EXPERIMENT RESULT AND ANALYSIS

A. Experimental Comparison for M.R.R.

Experimental comparison of data of non-cryo treated and cryo-treated has been carried out for each of the factors, i.e., M.R.R., Fx, Fy, Fz and surface roughness



Graph 1.1 (a) main effects plot for M.R.R. for the non-cryo-treated workpiece.



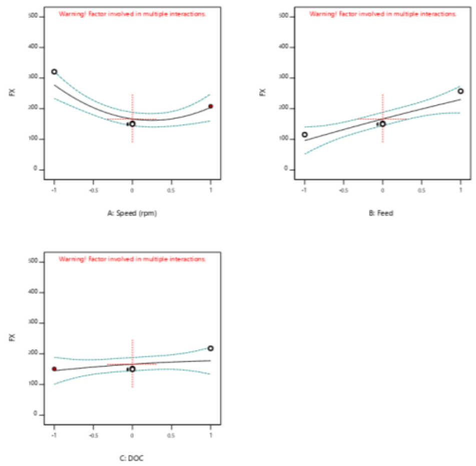
Graph 1.1 (b) Main effects plot for M.R.R. for the cryo-treated workpiece.

The above graphs show that M.R.R. is stable for the first two levels of speed and then start increasing as speed increases for non-treated workpieces. In contrast, cryo-treated workpieces show the opposite nature as it increases as speed is increasing up to mid-level and then gradually decreases. It clearly shows that cryogenic treatment gives better M.R.R. up to medium ranges of speed but shows a steady effect for higher speed.

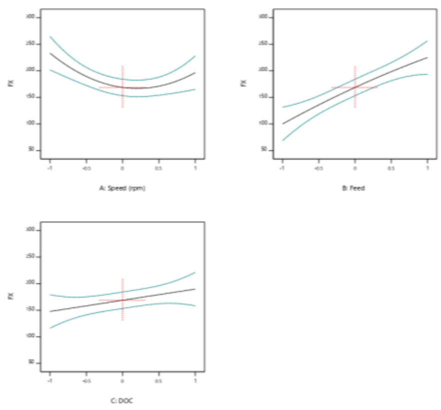
Non-treated workpieces do not indicate any significant effect for Feed. The gradually increasing and then decreasing curve shows mid-range feed value give high M.R.R. For Cryo-treated workpieces, it is exactly the opposite.

DOC has the same effect for both types of workpieces, i.e., M.R.R. increasing with DOC increase. Non-treated workpieces show gradual effect, whereas Cryo-treated has a continuous effect that is almost linear. So, for M.R.R., Cryogenic treatment gives better results than non-cryo treated workpieces for most of the parameters.

B. Experimental Comparison for Fx.



Graph 1.2 (a) Graph shows the main effects plot for Fx for the non-cryo-treated workpiece.



Graph 1.2 (b) Main effects plot for Fx for the cryo-treated workpiece.

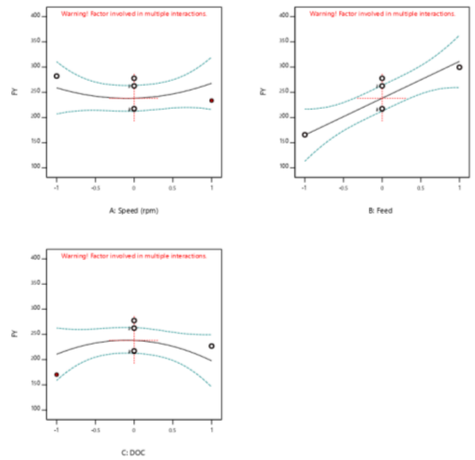
As per the above graphs, Force Fx decreases with an increase in speed up to mid-levels and then gradually increases as speed increases. But force value for cryo-treated workpieces is a little bit higher than non-treated workpieces, which indicates that cryogenic treatment increases axial force induced during machining, maybe because of more martensite in the matrix than that of the non-treated workpiece.

Feed w.r.t Fx shows a similar trend, i.e., increasing in nature, but here at the initial level, both types of workpieces show the same result Cryo-treated workpieces show a little higher value higher range of Feed.

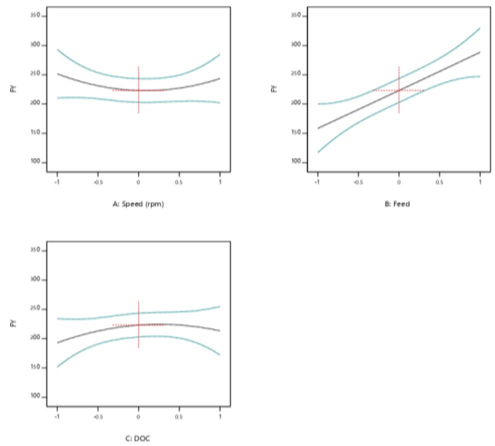
DOC w.r.t Fx also shows a similar kind of curve for both the types of workpieces, but again, the value of the cryo-treated workpiece has a little higher value than the non-treated one.

Overall results from the above graph indicate that axial forces rise because of cryogenic treatment and more martensite and decreased retained austenite.

C. Experimental Comparison for Fy.



Graph 1.3 (a) Graph shows the main effects plot for Fy for the non-cryo-treated workpiece.



Graph 1.3 (b) Graph shows the main effects plot for Fy for the cryo-treated workpiece.

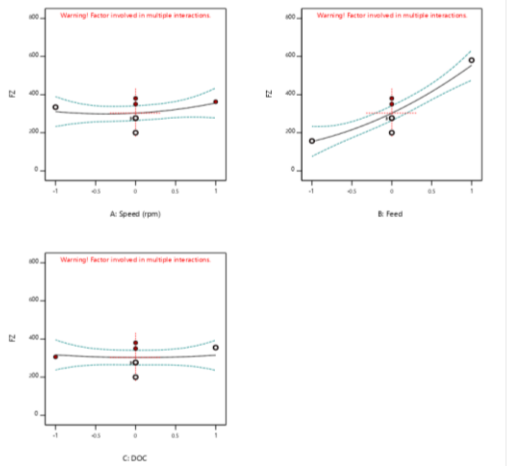
As per the above graphs, Force Fy decreases with an increase in speed up to mid-levels and then gradually increases as speed increases. For non-treated as well as cryo-treated workpieces Radial Force vs. Speed graph is the same. It means that the effect of cryogenic treatment is negligible on radial forces.

Like the Speed graph, Feed also shows the same curve for both the type of workpieces, and cryogenic treatment has a negligible effect on Feed.

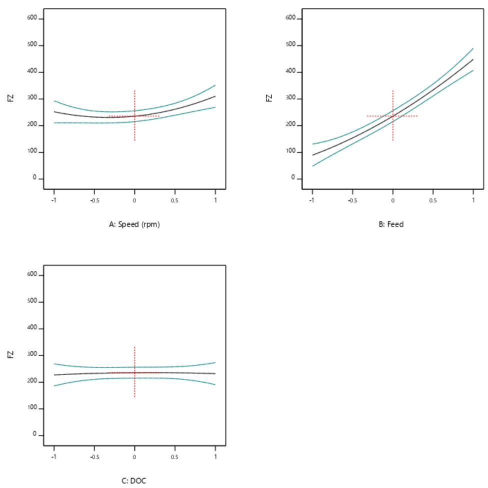
DOC also has the same nature of curve for non-treated and cryo-treated workpieces but with slight change at DOC's higher values. Non-treated workpiece shows a rapid decrease in Fy, whereas cryo-treated have a steady and linear curve at a higher level.

Overall results from the above graph indicate that radial forces have little effect w.r.t DOC, whereas it shows negligible effect w.r.t speed and feeds for non-treated as well as cryo-treated workpieces

D. Experimental Comparison for Fz.



Graph 1.4 (a) Graph shows the main effects plot for Fz for the non-cryo-treated workpiece.



Graph 1.4 (b) Graph shows the main effects plot for Fz for the cryo-treated workpiece.

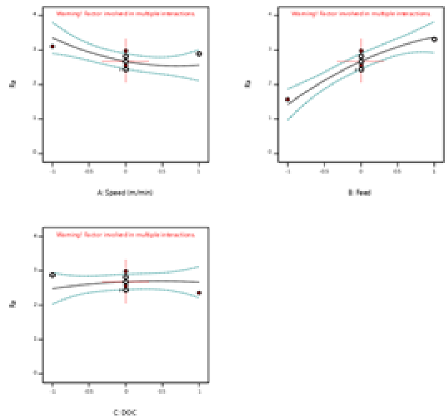
As per the above graphs, Force Fz decreases with an increase in speed up to mid-levels and then gradually increases as speed increases. Both show the same kind of curve, but the cryo-treated workpiece shows lower values of Fz than that of the non-treated workpiece.

For non-treated workpiece, tangential force starts at around 150 N at the lower level of Feed and around 600 N at higher Feed. In contrast, for the cryo-treated workpiece, tangential force starts at around 100 N at a lower level of Feed and around 450 N at a higher feed level. It shows that Fz values are lower for cryo-treated workpieces, which elucidates that cryogenic treatment has a significant effect on Fz as lower values are recommended.

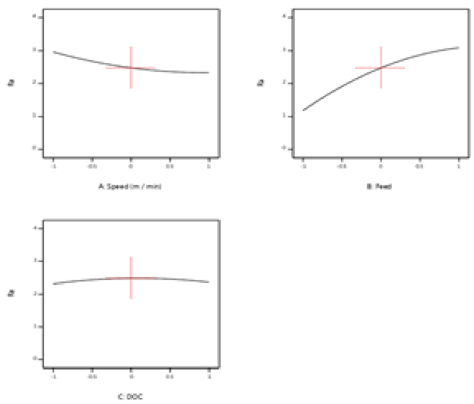
DOC also has the same nature of curve for non-treated and cryo-treated workpieces, but like speed and Feed, DOC also has lower values for the cryo-treated workpiece.

Overall results from the above graph indicate that cryogenic treatment has a significant effect on tangential forces for all the input parameters as lower force values are recommended.

E. Experimental Comparison for Ra.



Graph 1.5 (a) Graph shows the main effects plot for Ra for the non-cryo-treated workpiece.



Graph 1.5 (b) Graph shows the main effects plot for Ra for the cryo-treated workpiece.

As per the above graphs, Ra decreases as speed increases, but the cryo-treated workpiece has little bit lower Ra values than that of the non-treated workpiece.
Feed w.r.t Ra for non-cryo treated workpieces shows that the Ra increases as feed increases, Ra for both the type of workpiece increases. Cryo-treated workpieces have lower values than the non-treated ones.
DOC is decreasing slowly as feed increases, which are the same in both cases. Lower values of Ra are always recommended.

IV. EXPERIMENTAL DATA ANALYSIS

A. Response Surface Methodology - Regression analysis and ANOVA

To determine the best-suited equation connecting response with input variables, a regression technique has been used. ANOVA table is used to check the significance of the regression model. The value of R is termed as a regression coefficient. The value of R^2 is an important criterion to decide the validity of the regression model. If this value is 0.80 or more than that, the regression model's relationship is acceptable.

Table 2: Regression analysis and ANOVA for Non-cryo and cryo- treated workpiece

NON-CRYO-TREATED WORKPIECE			
Output Parameters	R2	P value	Significant Parameters
MRR	0.8587	0.0031	DOC
Fx	0.9149	0.0003	Speed, Feed
Fy	0.8520	0.0038	Feed
Fz	0.9474	<0.0001	Feed
Ra	0.9345	<0.0001	Speed, Feed

CRYO-TREATED WORKPIECE			
Output Parameters	R2	P value	Significant Parameters
MRR	0.9657	<0.0001	Speed, DOC
Fx	0.9350	<0.0001	Feed, DOC
Fy	0.8673	0.0023	Feed
Fz	0.9808	<0.0001	Speed, Feed
Ra	0.9612	<0.0001	Speed, Feed

From the above table, it is clear that Feed is the most significant parameter for the given set of experiments, followed by speed and DOC. All regression models are Significant. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve the model.

B. Regression Equations for Non-cryo and cryo-treated workpiece

Table 3: Regression equations for Non-cryo-treated Workpiece

MRR=	+3.37486 +0.562701 V (m/min) +0.295190 F + 1.39450 DOC -0.456404 V (m/min) * F(mm) +0.057332 V (m/min) * D(mm) +0.275321 F(mm) * D(mm) +0.659677 V^2 - 0.643423 F^2 -0.188053 D^2
Fx =	+166.42927 -36.77100 V +67.07900 Fe+ 16.158 D -8.06125 V * F -1.01375 V * D - 5.71375 F * D + 74.62682 V^2 -3.52318 F^2 -5.30818 D^2
Fy =	+238.19909 +4.52000 V +73.10000 F - 6.54000 D + 8.625 V * F +19.22500 V * D - 16.87500 F * D +25.17727 V^2 -0.022727 F^2 -34.02273 DOC^2
Fz =	+302.81636+22.45000 V +199.84000 F - 1.01000 D +39.41250 V * F +26.73750 V * D -6.13750 F * D +30.55909 V^2 +51.10909 F^2 +12.85909 D^2
Ra =	+2.69350 +0.375367 V +0.811100 F +0.201600 D -0.554458 V * F +0.408042 V * D +0.169292 F * D +0.144924 V^2 - 0.200742 F^2 -0.093242 D^2

Table 4: Regression equations for Cryo-treated Workpiece

MRR=	+3.39647 +0.305971 V +0.150453 F +1.45117 D - 0.084825 V * F +0.108832 V * D + 0.238567 F * D- 0.556293 V^2 + 0.323757 F^2 - 0.302050 D^2
Fx =	+168.75064 - 18.36000 V + 62.4910 F +21.05800 D + 1.55500 V * F + 18.005 V * D +0.04250 F * D + 46.24591 V^2 - 6.21909 F^2 - 0.054091 D^2
Fy =	+ 223.17491 - 4.10600 V + 64.95700 F +10.24500 D + 4.57625 V * F + 5.71125 V * D +0.366250 F * D +24.48273 V^2 +0.377727 F^2 - 19.94227 D^2
Fz =	+235.78064 +29.19600 V +179.61400 F + 2.370 D +13.20000 V * F + 24.95500 V * D - 8.3350 F * D +45.63591 V^2 +33.50591 F^2 -5.99409 D^2
Ra =	+2.47660 -0.3150 V ++0.96 F +0.0235 D +0.264 V * F +0.264 V * D -0.0260 F * D +0.1720 V^2 - 0.3450F^2 -0.1425 D^2

C. Response surface and Contour Plots Non-cryo treated Workpieces.

a) Contour and Surface plot for M.R.R. (Non-treated workpiece)

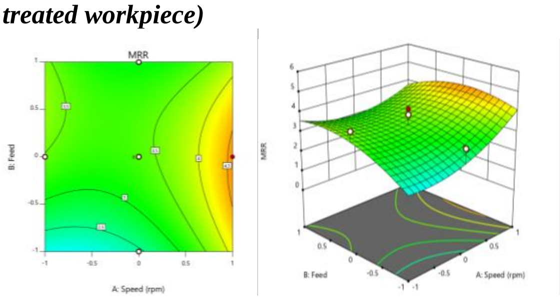


Fig 2.1 Contour and Surface plot for M.R.R. (Non-treated workpiece)

Fig shows contour as well as Response plot for M.R.R. w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on M.R.R. It has been observed that high M.R.R. is possible at high speed and medium feed level, which is indicated at the right mid-portion of the plot.

b) Contour and Surface plot for Fx (Non-treated workpiece)

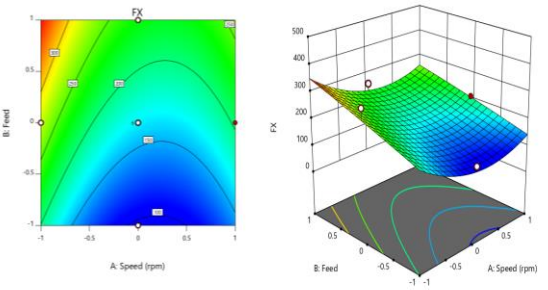


Fig 2.2 Contour and Surface plot for Fx (Non-treated workpiece)

Fig shows contour as well as Response plot for Fx w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Fx. Low Fx values are possible at low Feed and medium speed level indicated at a lower mid (blue colored) portion of the plot. Blue colored portion may be the optimum region for given input parameters as the lower value of Fx is recommended

c) Contour and Surface plot for Fy (Non-treated workpiece)

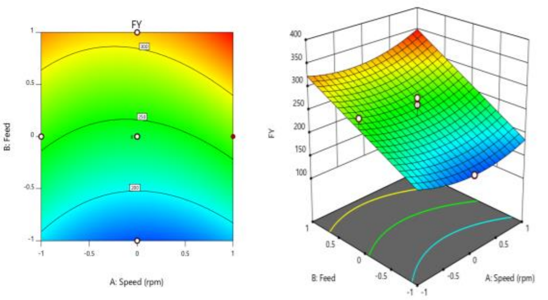


Fig 2.3 Contour and Surface plot for Fy (Non-treated workpiece)

Fig shows contour as well as Response plot for Fy w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Fy. Low Fy values are possible at low Feed and medium speed level indicated at a lower mid (blue colored) portion of the plot. Blue colored portion may be the optimum region for given input parameters as the lower value of Fy is recommended

d) Contour and Surface plot for Fz (Non-treated workpiece)

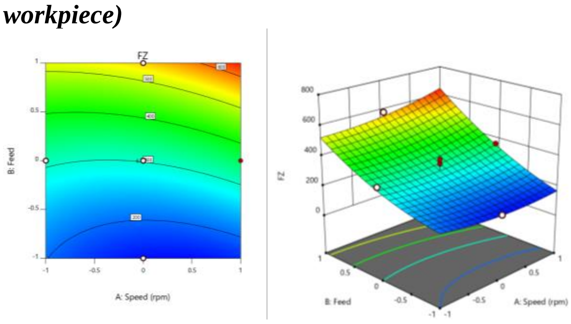


Fig 2.4 Contour and Surface plot for Fz (Non-treated workpiece)

Fig shows contour as well as Response plot for Fz w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Fz. Low Fz values are possible at low Feed and almost for all speed levels, indicated at the lower mid (blue colored) portion of the plot. Blue colored portion may be the optimum region for given input parameters as the lower value of Fz is recommended.

f) Contour and Surface plot for Ra (Non-treated workpiece)

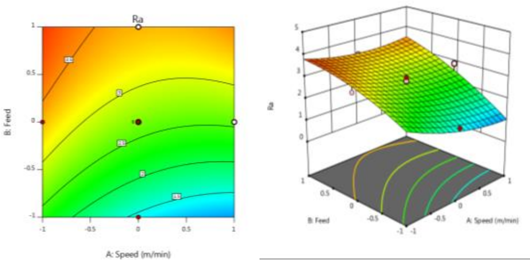


Fig 2.5 Contour and Surface plot for Ra (Non-treated workpiece)

Fig shows contour as well as Response plot for Ra w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Ra. It has been observed that low Ra values are possible at low Feed and high-speed level, indicated at the lower right (blue colored) portion of the plot. Ra is drastically decreasing with an increase in speed and lowering Feed. A lower value of Ra is recommended.

D. Response surface and Contour Plots for cryo treated workpiece.

a) Contour and Surface plot for M.R.R. (Cryo-treated workpiece)

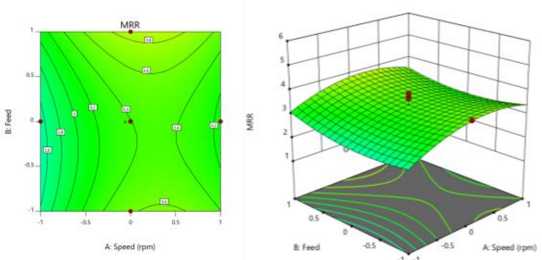


Fig 3.1 Contour and Surface plot for M.R.R. (Cryo-treated workpiece)

Fig shows contour as well as Response plot for M.R.R. w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on M.R.R. It has been observed that high M.R.R. is possible at medium speed and high feed level, indicated at the upper mid-portion of the plot.

b) Contour and Surface plot for Fx (Cryo-treated workpiece)

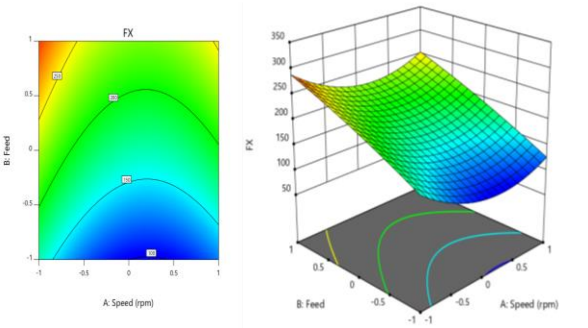


Fig 3.2 Contour and Surface plot for Fx (Cryo-treated workpiece)

Fig shows contour as well as Response plot for Fx w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Fx. Low Fx values are possible at low Feed and medium speed level indicated at the lower mid (blue colored) portion of the plot. The blue colored portion may be the optimum region for given input parameters as the lower Fx value is recommended.

c) Contour and Surface plot for Fy (Cryo-treated workpiece)

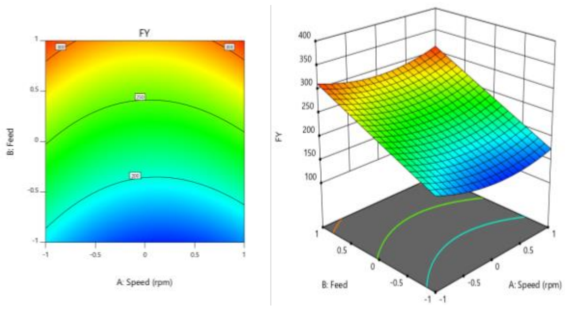


Fig 3.3 Contour and Surface plot for Fy (Cryo-treated workpiece)

Fig shows contour as well as Response plot for Fy w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Fy. Low Fy values are possible at low Feed and medium speed level indicated at the lower mid (blue colored) portion of the plot. Blue colored portion may be the optimum region for given input parameters as a lower Fy value is recommended.

d) Contour and Surface plot for Fz (Cryo-treated workpiece)

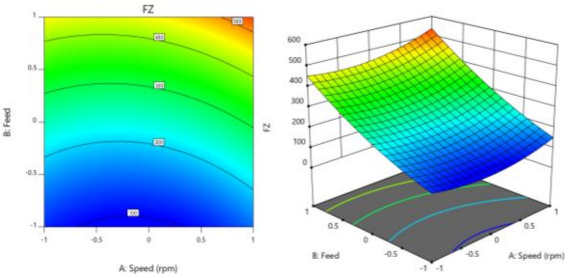


Fig 3.4 Contour and Surface plot for Fz (Cryo-treated workpiece)

Fig shows contour as well as Response plot for Fz w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Fz. Low Fz values are possible at low Feed and almost for all speed levels, indicated at the lower mid (blue colored) portion of the plot. Blue colored portion may be the optimum region for given input parameters as the lower value of Fz is recommended.

e) Contour and Surface plot for Ra (Cryo-treated workpiece)

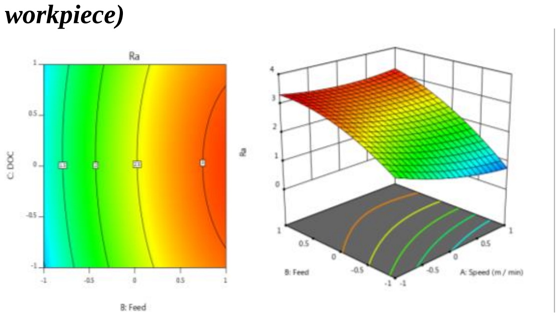


Fig 3.5 Contour and Surface plot for Ra (Cryo-treated workpiece)

Fig shows contour as well as Response plot for Ra w.r.t Speed and Feed. These plots show the quantified effect of function part of speed and feed on Ra. It has been observed that low Ra values are possible at low Feed and high-speed level, indicated at the lower right (blue colored) portion of the plot. Ra is drastically decreasing with an increase in speed and decreasing Feed. A lower value of Ra is recommended.

V. OPTIMIZATION

Grey Relational Analysis

The grey analysis was first proposed many decades ago but has been extensively applied only in the last decade. Grey analysis has been broadly applied in optimizing the performances involving multiple responses

However, data to be used in Grey analysis must be pre-processed into quantitative indices for normalizing raw data for another analysis. Pre-processing raw data is converting an original sequence into a decimal sequence between 0.00 and 1.00 for comparison. Based on the Higher, the better and the smaller, the better criteria, Output parameters are optimized.

Table No.3: Optimum values of Output parameters for cryo and non-cryo-treated workpiece using G.R.A.

Experiment set up	***SPEED*** (m/min)	***FEED*** (mm/rev)	***DOC*** (mm)	***GRG***	R^2
For Non-treated workpiece	***135***	***0.2***	***0.5***	***0.872***	***0.881***
For Cryo-treated workpiece	***135***	***0.2***	***0.5***	***0.993***	***0.893***

From the above table, the highest grey relational coefficient is 0.993, i.e., for a combination of velocity 235 m/min, feed 0.2 mm, and Doc 0.5 mm. But optimum value shows different combinations, i.e., velocity 135m/min, feed 0.2mm, and Doc 0.5mm. So, the optimum value may lie between these two ranges.

VI. CONCLUSIONS

- It is observed that the tangential cutting forces are higher than that of the axial and radial components of cutting forces. The axial component of force decreases with an increase in cutting speed, but the other two components do not significantly change with the change in cutting speed.
- If speed is high at lower Feed, surface roughness should be low, and observations show the same. Machine instability at higher speeds might be the reason for it.
- Surface roughness was found to be highest at higher Feed and higher Depth of cut. As speed and Feed show a significant effect on M.R.R., M.R.R. increases as both the component increases.
- Material Removal Rate increases almost linearly with the Feed and higher values of the Speed and Depth of cut.
- Cryogenically treated workpieces show better results as far as the material removal rate is concerned.
- At initial levels, the value of the axial component of force Fx is almost the same for both types of workpieces, but Fx's value for cryo-treated workpieces is higher.
- Fy's radial component shows almost the same trend for both types of workpieces; however, cro-treated workpieces' values are lesser compared to non treated.
- The cryogenic treatment has a significant effect on tangential cutting force component Fz for all input parameters. Fz value is lesser for cryo-treated workpieces at all the levels.
- Multi-objective optimization using Technique, I.e., Grey Relational Analysis (G.R.A.), has been proposed and used for the optimization which basically fuses the responses based on their weightage the optimum response. Optimum values of parameters calculated by this method were the same for both the types of the workpiece, i.e., speed is 135 m/min, Feed is 0.2rev/min, and 0.5mm is Depth of cut.

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