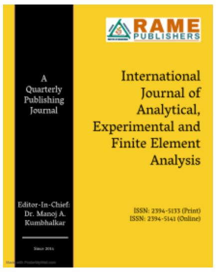

International Journal of Analytical, Experimental and Finite Element Analysis
Vol. 7, Issue. 2, July 2020, pp 19 - 27
https://doi.org/10.26706/ijaefea.2.7.20200602

Investigation of the Effect on Surface Roughness of Cryogenic Process Applied to Cutting Tool

Furgan BAYRAKTAR[1]
Master Student
bayraktarfurgan@gmail.com

Fuat KARA[2]
Associate Professor
fuatkara@duzce.edu.tr

Düzce University
Düzce / Turkey

Abstract— **As the cryogenic treatment is the most harmless mechanical healing process in terms of both environmentally friendly and human health, its usage is increasing day by day. In this study, the effect of deep cryogenic process applied on cutting tool material on surface roughness parameters will be investigated. In this context, Sleipner cold work tool steel will be used as workpiece material and PVD (physical vapour decomposition) coated carbide tools will be used as cutting tool. Cutting tool material will be deep cryogenic at -180 °C. A total of 36 cutting tests will be performed for two different cutting tools (untreated, treated) in three different cutting speeds (40, 60, 80 m/min) and three different feed rates (0.04, 0.06, 0.08 mm/rev) combinations. In this study, Taguchi analysis was applied to experimental data. However, analysis of variance, linear and multiple regression analysis were performed. As a result, the effect of the cryogenic process applied to the cutting tool material was examined both experimentally and statistically.**

Index Terms—Cryogenic process, sleipner, surface roughness, carbide tool

I. Introduction

In the cryogenic process, the materials are cooled to very low temperatures (-196 ºC) to achieve the desired metallurgical and microstructural properties. The reduction of these temperatures is possible by feeding the system to computer or electronic circuit controlled liquid nitrogen (N2) and using the most suitable insulation materials. The cryogenic process is divided into two as “deep” and “shallow”. In shallow cryogenic process, the temperature of the materials is lowered to around -150 ºC. Despite a significant improvement in the mechanical properties of the materials, the desired properties may not be fully achieved. In the deep cryogenic process, the materials are cooled down to -196 ºC, the effects of this process increase significantly compared to the shallow cryogenic process. Since liquid nitrogen and the part do not come into contact with each other, there is no change in part sizes and the risk of cracking in the part is eliminated. This special process is not a surface treatment, but the same effect is created at every point of the material. As a result of microstructural changes, the strength, toughness and hardness of the materials increase and the abrasion resistance increases. Especially the increase in abrasion resistance catches 800% according to the type of material. As a result, the material life is significantly increased. The cryogenic process, which is widely applied in Europe and America, has become widespread abroad with the presence of large companies. Despite the cryogenic process in Turkey has not implemented enough so despite the superior properties and to gain an awareness of the purpose of these studies it. [1].

Considering that the metal removal is based on the contact of two metals, tool wear is inevitable. When cutting takes place in the form of the hard tool abrading the less hard tool, a worn tool loses its feature. In this case, cutting will take place in bad conditions, and therefore unexpected situations arise in the product. In this context, it is extremely important to know the tool life of the cutting tool and continue the chip

Research Article
Published online – 30 July 2020

Cite this article – Furgan BAYRAKTAR and Fuat KARA, “Investigation of the Effect on Surface Roughness of Cryogenic Process Applied to Cutting Tool”, *International Journal of Analytical, Experimental and Finite Element Analysis*, RAME Publishers, vol. 7, issue 2, pp. 19-27, 2020.
https://doi.org/10.26706/ijaefea.2.7.20200602

removal process with a new cutting tool as soon as the wear takes place. The useful machining time of a tool is the total time that the insert remains on the workpiece. By controlling the abrasions occurring at the tip during this time the tool life is reduced, the deviations in the dimensions occur, making it difficult to control the measurement and prevent the processed surfaces from coming out of order. Due to cutting tool wear during machining, cutting tool life and machining time are very important to ensure the highest productivity. Suitable cutting tool and cutting parameters; quality production, sensitive surface quality, determination of the most suitable loom power and economics are important for achieving the most appropriate result. In order to work at higher cutting speeds and increase the amount of production, hard metal inserts are used and a wide range of research is done on the performance of these inserts. One of the most important problems encountered in machining is that cutting tool wear cannot be detected in a timely manner. In metal cutting with a worn cutting tool, it becomes very difficult to obtain the desired part dimensions and surface quality as well as the damages that the cutting tool can cause to the machine. In addition, the increase of resistance forces acting on the cutting tool, which has lost its sharpness, will also increase the stock removal forces required for cutting. Tool wear is one of the most important factors that also affect surface roughness. For these reasons, cutting tool wear is one of the most important criteria to be considered due to its effect on the efficiency of the cutting process. In machining, it must be replaced during the cutting process before the tool life is complete. Therefore, it is necessary to know in advance how long a cutter will be used. During the cutting process, friction, heat, force, etc. Due to factors, many negative situations arise on the cutting tool. These adversities cause abrasions on the end and side surfaces of the cutting tool. Abrasions occurring on the insert and the side surface will cause deterioration in the surface quality, and continuing production without changing the cutting tool will increase production and tool costs. Tool wear is inevitable, but it does not have much negative impact if it is known when and how much wear occurred and what kind of wear. If the cutting tool materials are used correctly, the chip removal process will not only be much more efficient and economical, it will become a much more reliable and continuous process [2].

The cryogenic process is a complementary process to improve the properties of metals used in recent years. In the 1930s and 1940s, this process has been shown to improve the performance of tool steels. Some researchers have agreed that cryogenic processing can also improve the performance of teams. Improved wear resistance of tool steels is the most important effect of this process. Some industries such as space, electronics and automotive have used this process on the production line to improve the wear resistance and dimensional stability of parts.

More than a century has passed since the development of carbon steels, the first cutting tool material suitable for use in metal cutting. A large number of different cutting tool materials have been continuously developed since then. The industry is the driving force behind cutting material development, as there is always a need to increase productivity, process materials that are difficult to process, switch to unmanned machining operations and improve quality. The life of cutting tools plays an important role in increasing efficiency and is therefore an important economic factor. The approach used widely in the past to increase the life of the cutting tools has been heat treatment of tool materials. Although the cryogenic process, which is a complementary process to the conventional heat treatment, is a known method, its correct use compared to the heat treatment is at the initial stage.

Gill et al. conducted a comparative investigation of the wear behavior of tungsten carbide inserts with cryogenic process in dry and wet orthogonal turning to understand the effect of coolant. Uncoated square tungsten carbide inserts with chip breaker were provided and cryogenic at -196 ºC. Cutting experiments were carried out in accordance with ISO 3685-1993 under continuous and discrete processing conditions. The criterion chosen to determine the tool life is based on the maximum flank wear (0.6 mm) and the choice of cutting conditions should ensure sufficient wear at a suitable time interval. The results showed that the tungsten carbide inserts undergoing cryogenic treatment performed significantly better in wet turning conditions, especially at high cutting speeds, both under continuous and intermittent machining conditions. At the same time, a noticeable increase in tool life has been noted in batch machining conditions compared to continuous machining [3]

The cryogenic process is a complementary process to the classical heat behavior process in steels. Unlike coatings, it is a one-time, inexpensive and permanent process that affects the entire part of the part. Mohan Lal et al. performed a study on the importance of cryogenic process parameters in different materials and their improvement on tool wear. As a result of the experiments, it has been observed that the cryogenic process provides superiority to TiN coatings with an improvement of tool life of approximately 110% [4].

Experiments were performed according to the Taguchi L_{18} orthogonal array and signal/noise (S/N) ratios were used in the evaluation of the test results. In this study, experiments were carried out with and without applying deep cryogenic process to the cutting tool material. No such study was encountered during the literature research. Thus, it was aimed to make a different study from the previous studies.

II. Material And Method

In this study, Sleipner cold work tool steel, having a traditional heat treated 50-52 HRc hardness value, was processed with two different PVD coated carbide cutting tools with and without cryogenic treatment. The cryogenic process was performed as -196 ºC deep cryogenic process for 36 hours. Then, by comparing the surface roughness parameters, it was aimed to determine the effects of the cryogenic process.

The chemical components of the Sleipner cold work tool steel used in this study were given in table I. The experiments were carried out by turning the steel bars prepared in Ø70x250mm lengths on the CNC bench.

Taegutec WNMG 080408 MT TT5080 will be used as cutting tool. Cutting tools were given in fig.1 and technical specifications in table II.

TABLE I

Chemical composition of Sleipner steel

%C	%Si	%Mn	%Cr	%Mo	%V
0.90	0.90	0.50	7.8	2.5	0.50

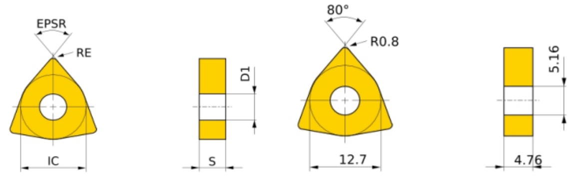

Fig.1: Cutting tools

TABLE II

Cutting tool features

Cutting Tool	WNMG
Standard	DIN 844
Cutting Tool Material	Tungsten Carbide
Coating Materials	TiAlN
Hardness	60-85 HRc
Type of Use	Turning

The cutting experiments were carried out using three different feed rates (0.04, 0.06 and 0.08 mm/rev) and three different cutting speeds (40, 60 and 80 m/min), keeping the depth of cut constant (2 mm). As a result of the experiments, surface roughness measurements were made by using Mahr Marsurf PS 10 Portable surface measuring device. The surface roughness (Ra) value was calculated as the average of five measurements taken from the machined surfaces.

In order to reach the correct result in experimental studies, it is necessary to design the correct experiment. In the study, Taguchi method was used as experimental design and analysis method. In this approach, developed by Dr. Genichi Taguchi, a statistical performance measure known as the S/N ratio is used to analyze the results. The results obtained from the experiments are converted to signal/noise ratio (S/N) and the evaluation are made. S/N ratio refers to S signal factor, N refers to noise factor. The signal factor refers to the actual value received from the system, and the noise factor refers to the factors that cannot participate in the design of the experiment but affect the result of the experiment. Noise sources are all variables that cause the performance characteristics to be obtained to deviate from the target value [5]. In calculating S/N ratios; Depending on the characteristic type, the nominal is the best, the largest is the best, and the smallest is the best method [6-8]. In determining the S/N values in this study, since the Ra value is desired to be the smallest in terms of processing efficiency, the principle of “the smallest best” given in Equation (1) the corresponding formula is used. Here; yi refers to the measured surface roughness and vibration value, and n refers to the number of tests carried out. Cutting parameters are selected as cutting tool type (Ct), cutting speed (V) and feed rate (f).

$$S/N = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} yi^2\right) \quad (1)$$

III. Results And Discussion

A. Experimental Results

The surface roughness values obtained according to different cutting speeds and feed rates were given in graphs. Fig. 2 - 4 show the surface roughness values obtained according to different cutting speeds in constant feed rate.

In Fig. 2, the surface roughness values of feed rate of 0.04 (mm/rev), 40 (m/min) cutting speed, 0.489 µm on the surface treated with untreated-ct. It was measured as 0.321 µm on the surface treated with treated-ct. When the cutting speed was 60 (m/min), untreated-ct was measured at 0.668 µm, treated-ct 0.473 µm. When the cutting speed was 80 (m/min), untreated-ct was measured as 0.798 µm, treated-ct 0.907 µm. When the cutting speed increased to 60 the untreated-ct surface roughness value increased by 36% and treated-ct increased by 47%.

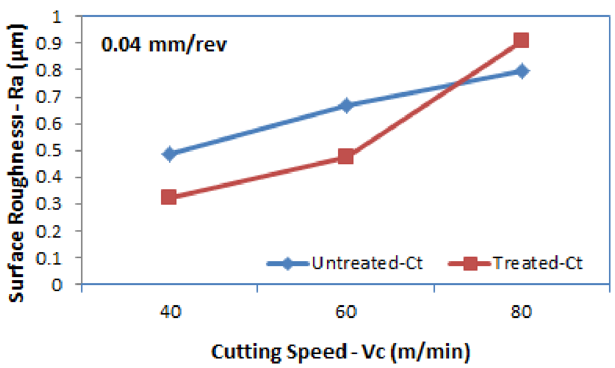

Fig.2: Change of Ra depending on cutting speed for 0.04 mm/rev

When cutting speed increased to 80 untreated-ct increased by 19%, treated-ct increased by 92%. When these three parameters are evaluated, when the cutting speed increased from 40 to 80, the untreated-ct surface roughness value increased by 63% and treated-ct surface roughness value increased by 183%.

In Fig. 3, the surface roughness values of feed rate of 0.06 (mm/rev), 40 (m/min) cutting speed, 0.734 µm on the surface treated with untreated-ct. It was measured as 0.623 µm on the surface treated with treated-ct. When the cutting speed was 60 (m/min), untreated-ct was measured at 0.876 µm, treated-ct 0.759 µm. When the cutting speed was 80 (m/min), untreated-ct was measured as 1.225 µm, treated-ct 1.528 µm. When the cutting speed increased to 60 the untreated-ct surface roughness value increased by 19% and treated-ct increased by 22%. When cutting speed increased to 80 untreated-ct increased by 40%, treated-ct increased by 101%. When these three parameters are evaluated, when the cutting speed increased from 40 to 80, the untreated-ct surface roughness value increased by 67% and treated-ct surface roughness value increased by 145%.

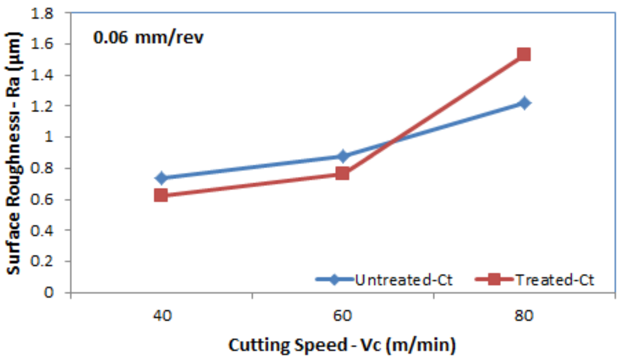

Fig.3: Change of Ra depending on cutting speed for 0.06 mm/rev

In Fig. 4, the surface roughness values of feed rate of 0.08 (mm/rev), 40 (m/min) cutting speed, 0.923 µm on the surface treated with untreated-ct. It was measured as 0.761 µm on the surface treated with treated-ct. When the cutting speed was 60 (m/min), untreated-ct was measured at 1.218 µm, treated-ct 1.014 µm. When the cutting speed was 80 (m/min), untreated-ct was measured as 2.996 µm, treated-ct 1.923 µm. When the cutting speed increased to 60 the untreated-ct surface roughness value increased by 32% and treated-ct increased by 33%. When cutting speed increased to 80 untreated-ct increased by 146%, treated-ct increased by 90%. When these three parameters are evaluated, when the cutting speed increased from 40 to 80, the untreated-ct surface roughness value increased by 225% and treated-ct surface roughness value increased by 153%.

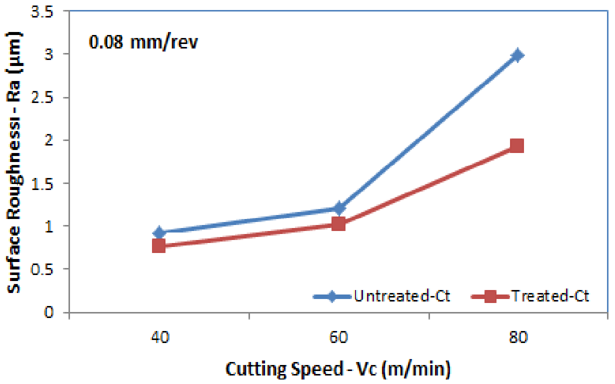

Fig.4: Change of Ra depending on cutting speed for 0.08 mm/rev

Fig. 5-7 shows the surface roughness values obtained according to different feed rates at constant cutting speed. In Fig. 5, surface roughness values at a cutting speed of 40 (m/min) and feed rate of 0.04 (mm/rev) are 0.489 µm on the surface treated with untreated-ct. It was measured as 0.321 µm on the surface treated with treated-ct. When the feed rate was 0.06 (mm/rev), untreated-ct was measured 0.734 µm, treated-ct 0.623 µm. When the feed rate was 0.08 (mm/rev), untreated-ct 0.923 µm, treated-ct 0.761 µm were measured. When the feed rate increased to 0.06 the untreated-ct surface roughness value increased by 50% and treated-ct increased by 94%. Untreated-ct increased by 26% and treated-ct increased by 22% when the feed rate increased to 0.08.

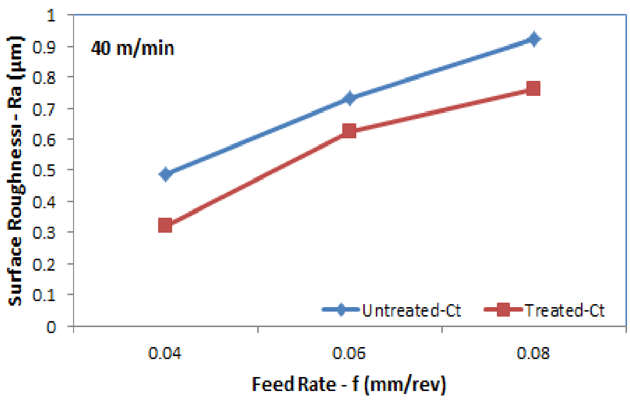

Fig.5: Change of Ra depending on feed rate for 40 m/min

When these three parameters are evaluated, when the feed rate increased from 0.04 to 0.08 untreated-ct surface roughness value increased by 89%, treated-ct surface roughness value increased by 137%.

In Fig. 6, surface roughness values at a cutting speed of 60 (m/min) and feed rate of 0.04 (mm/rev) are 0.668 µm on the surface treated with untreated-ct. It was measured as 0.473 µm on the surface treated with treated-ct. When the feed rate was 0.06 (mm/rev), untreated-ct was measured 0.876 µm, treated-ct 0.759 µm. When the feed rate was 0.08 (mm/rev), untreated-ct 1.218 µm, treated-ct 1.014 µm were measured. When the feed rate increased to 0.06 the untreated-ct surface roughness value increased by 31% and treated-ct increased by 60%. Untreated-ct increased by 39% and treated-ct increased by 34% when the feed rate increased to 0.08. When these three parameters are evaluated, when the feed rate increased from 0.04 to 0.08 untreated-ct surface roughness value increased by 82%, treated-ct surface roughness value increased by 114%.

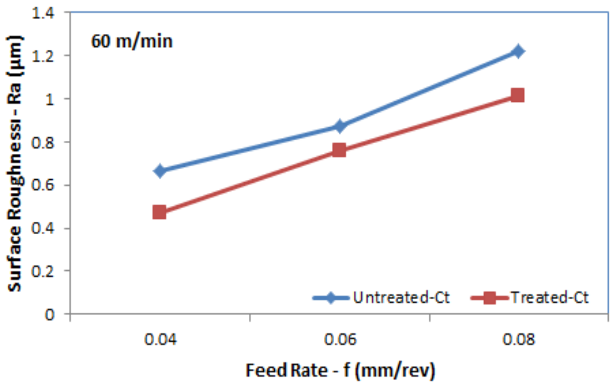

Fig.6: Change of Ra depending on feed rate for 60 m/min

In Fig. 7, surface roughness values at a cutting speed of 80 (m/min) and feed rate of 0.04 (mm/rev) are 0.798 µm on the surface treated with untreated-ct. It was measured as 0.907 µm on the surface treated with treated-ct. When the feed rate was 0.06 (mm/rev), untreated-ct was measured 1.225 µm, treated-ct 1.528 µm. When the feed rate was 0.08 (mm/rev), untreated-ct 2.996 µm, treated-ct 1.923 µm were measured. When the feed rate increased to 0.06 the untreated-ct surface roughness value increased by 54% and treated-ct increased by 68%. Untreated-ct increased by 145% and treated-ct increased by 26% when the feed rate increased to 0.08. When these three parameters are evaluated, when the feed rate increased from 0.04 to 0.08 untreated-ct surface roughness value increased by 275%, treated-ct surface roughness value increased by 112%.

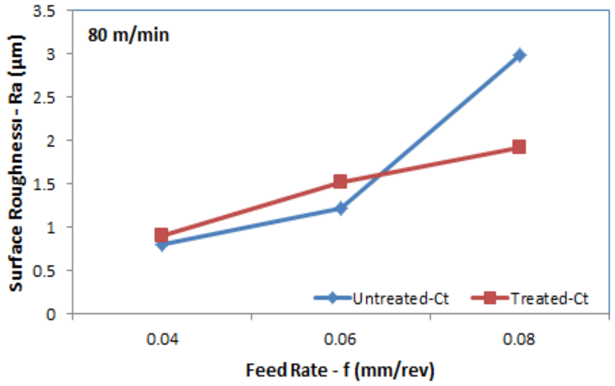

Fig.7: Change of Ra depending on feed rate for 80 m/min

The graphs show that increased cutting speed increases the surface roughness value (Ra). This has been linked to increased cutting speed, increased vibration on the cutting tool, thus increasing the temperature in the cutting zone and increasing the surface roughness of the tool by wearing [9]. If a general evaluation is made for Figure 4-7, lower surface roughness values were achieved using the cryogenically treated cutting tools. This finding was linked to the enhanced hardness and abrasive wear resistance of the DCT inserts following cryogenic treatment. It is accepted that surface roughness values rise as a result of deterioration of the cutting insert geometry caused by tool wear [7].

B. Statistical Analysis

1. Taguchi analysis

The S/N ratios calculated on the basis of the Ra values obtained as a result of the hard machining tests performed on the Sleipner cold work tool steel according to the Taguchi L_{18} test design were given in Table III.

The S/N responses generated by the Taguchi method were used to determine the most effective of the control factors on the optimum levels and performance characteristics (surface roughness). The highest S/N values in this table show the optimum level of each control factor. The S/N responses showing the effect of each control factor on surface roughness were given in Table IV.

TABLE III

THE EXPERIMENTAL RESULTS AND S/N RATIOS VALUES

Exp. no	(A) Ct	(B) V (m/min)	(C) f (mm/rev)	Ra (µm)	Ra - S/N ratio (dB)
1	Untreated-Ct	40	0.04	0.489	6.21382
2	Untreated-Ct	40	0.06	0.734	2.68608
3	Untreated-Ct	40	0.08	0.923	0.69597
4	Untreated-Ct	60	0.04	0.668	3.50447
5	Untreated-Ct	60	0.06	0.876	1.14992
6	Untreated-Ct	60	0.08	1.218	-1.71295
7	Untreated-Ct	80	0.04	0.798	1.95994
8	Untreated-Ct	80	0.06	1.225	-1.76272
9	Untreated-Ct	80	0.08	2.996	-9.53084
10	Treated-Ct	40	0.04	0.321	9.86990
11	Treated-Ct	40	0.06	0.623	4.11024
12	Treated-Ct	40	0.08	0.761	2.37231
13	Treated-Ct	60	0.04	0.473	6.50278
14	Treated-Ct	60	0.06	0.759	2.39516
15	Treated-Ct	60	0.08	1.014	-0.12076
16	Treated-Ct	80	0.04	0.907	0.84785
17	Treated-Ct	80	0.06	1.528	-3.68247
18	Treated-Ct	80	0.08	1.923	-5.67959

TABLE IV

S/N RESPONSE TABLES

Level	Ct	V (m/min)	f (mm/rev)
1	0.3560	4.3247	4.8165
2	1.8462	1.9531	0.8160
3		-2.9746	-2.3293
Delta	1.4902	7.2994	7.1458
Rank	3	1	2

When Table IV is examined, it can be seen that the most effective factors were the cutting speed, feed rate and cutting tool type, respectively. These results were confirmed by ANOVA. Moreover, the optimum surface roughness for the hard machining of the Sleipner cold work tool steel was obtained at the second level (A2) of the cutting tool type, at the first level (B1) of the cutting speed and at the first level (C1) of the feed rate.

The main effect graph showing the optimum values of the control factors, i.e., the machining parameters, is given in Fig. 8 As in the S/N response table; the highest S/N values in the main effect graph show the optimum level for that parameter. Thus, the optimum values for the surface roughness determined for the cutting tool type, cutting speed and feed rate was the treated cutting tool, 40 m/min and 0.04 mm/rev, respectively.

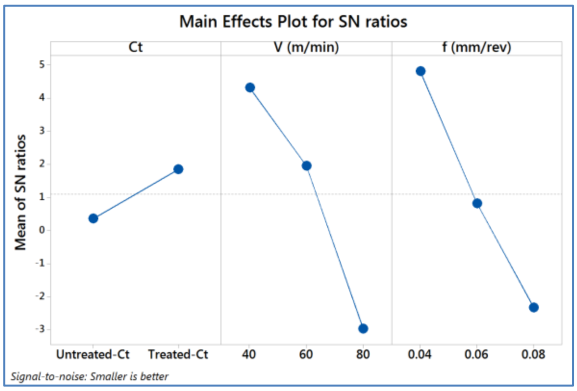

Fig. 8: Main effects plot of S/N ratios for Ra

2. Analysis of variance (ANOVA)

A variance analysis was performed to determine how all the control factors used in the experimental design influenced each other, what effect this had on the performance characteristics, and what kind of changes occurred in the performance characteristics at the different levels of the parameters. The ANOVA results for the effect levels of the control factors on Ra are given in Table V. In this table, firstly P value of significance is examined. If $p > 0.05$, there is no significant difference between the machining parameters. If $p < 0.05$, it is understood that there is a meaningful difference between the machining parameters in terms of the characteristics examined (Ra). In Table V, it is seen that there is a significant difference between the machining parameters because $p < 0.05$ for feed rate and cutting speed parameters. In addition, the F values and the percentage contribution ratio (PCR) showing the significance level of each variable can be seen. This analysis was performed at a 95% CI and 5% significance level. The effect of the control factors was determined by comparing the F values. The F factor is the biggest factor and has the most influence on the result.

TABLE V

ANOVA TABLE FOR RA

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Ct	1	0.1454	2.16%	0.1454	0.1454	1.18	0.299
V (m/min)	2	2.8313	42.14%	2.8313	1.4157	11.48	0.002
f (mm/rev)	2	2.2630	33.68%	2.2630	1.1315	9.18	0.004
Error	12	1.4792	22.02%	1.4792	0.1233		
Total	17	6.7189	100.00%				

According to the ANOVA results, the most important parameter affecting the surface roughness was found to be the cutting speed (42.14%). Following the cutting speed was the feed rate (33.68%), while the cutting tool type was effective on Ra at low levels (2.16%). The results of the S/N responses in Table IV and the results of the main effect graphs in Fig. 8 were verified by ANOVA.

3. Multiple regression analysis of surface roughness

In this study, multiple regression analysis was used to obtain the predictive equations (for both linear and quadratic regression models) for Ra, as seen in Equations (2). The independent variables that used analyses were cutting tool (Ct), cutting speed (V) and feed rate (f), whereas the dependent variables were surface roughness (Ra).

$$Ra = -1.393 - 0.180\,Ct + 0.02303\,V + 21.58\,f \qquad (2)$$

The R^2 values of the equations obtained by the linear regression model for Ra was found to be 0.73. The predictive equations for the quadratic regression of Ra is given below in Equations (3).

$$Ra = 3.11 + 0.523\,Ct - 0.0984\,V - 32.5\,f + 0.000669\,V^2 + 209\,f^2 - 0.00183\,CtV - 9.88\,Ctf + 0.731\,Vf \qquad (3)$$

The R^2 values of the equations obtained by the quadratic regression model for Ra was found to be 0.90. Hence, the predicted values obtained via the quadratic regression model were more extensive compared to those of the linear regression model. As a result, the quadratic regression model was considered as successful for the estimation of Ra. The statistical results obtained through quadratic regression analysis for the Ra in Fig. 9.

In Fig. 9 were given statistical results for Ra. In figure B, showing the normal probability plot vs. the residuals of the quadratic models, it can be seen that the residuals are arranged in a relatively straight line. This denoted a normal distribution of errors and signified that the terms stated in the model were significant. Moreover, a good correlation was found between the experimental vs. predicted Ra values [10].

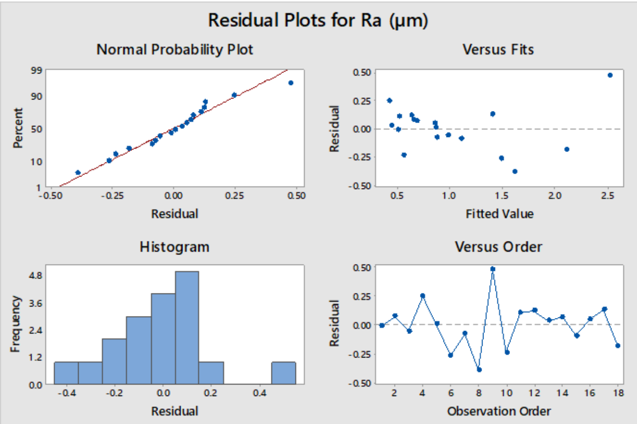

Fig. 9: Statistical results

Fig. 10 shows the measured and predicted responses, respectively, and reveal their differences. The values produced by the quadratic regression model were closer to the experimental findings for Ra. Accordingly, compared to the linear regression model, the ability of the quadratic models to represent the system within the scope of a specified experiment is illustrated in this figure.

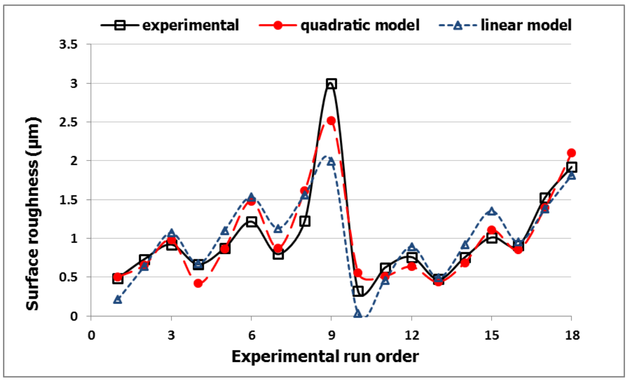

Fig. 10: Comparison between measured and predicted values

IV. Conclusions

In this study, a series of hard turning experiments were carried out to process conventional heat-treated sleipner cold work tool steel using cryogenically treated PVD coated carbide tools under different machining parameters. The experiments were designed according to the Taguchi L_{18} orthogonal array. In addition, the effects of the machining parameters on the surface roughness were determined via ANOVA. However, multiple regression analysis was performed to estimate experimental results. The results obtained are listed below.

- The application of cryogenic treatment to the cutting tool positively affected the surface roughness. The cutting tools that were cryogenically treated generally had lower Ra values than the untreated cutting tools.
- Surface roughness has also increased with an increase in both cutting speed and feed rate.
- The optimum values were obtained by taking the highest values of the average S/N ratios, thus determining the best result for Ra to be the second level of cutting tool type (treated-Ct), the first level of cutting speed (40 m/min) and the first level of feed rate (0.04 mm/rev).
- According to the ANOVA results, the most effective parameter on the Ra was the cutting speed (42.14%), followed by the feed rate (33.68%), and the cutting tool type (2.16%).
- Among the regression models, quadratic regression analysis showed the best correlation coefficient. Correlation coefficients were 0.73 and 0.90 for linear and quadratic regression, respectively.

The optimization results demonstrated that the Taguchi experimental design method had been successfully applied to determine the optimum surface roughness of the sleipner cold work tool steel in the hard-turning operation.

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