Investigating the Surface Roughness of Hardened Tool Steel (2379) during Face Milling Operation

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***Abstract*—The quality of a product is partly a function of its surface finish. This work considers the investigation of the surface roughness of a hardened tool steel during face milling operation. The design of experiment was carried out using the Taguchi approach and this was validated via physical experimentations. The physical experiments were carried out on Deckel Maho milling machine using a SANDVIK indexable cutting tool (R390-11 T3 08M-PM 1010) on a 2379 tool steel for press tools. The process parameters considered were the cutting speed, feed per tooth and depth of cut under different cutting conditions, which includes air-cooling and soluble oil cooling. The results obtained indicate that cutting operations under soluble oil cooling condition gave a better surface finish as compared to the cutting operations under air-cooling. The optimum combination of the process parameters, which produced the least surface roughness under the air cooling and soluble oil cooling conditions, are: cutting speed (125 m/min), feed per tooth (0.08 mm) and depth of cut (0.5 mm). It is envisaged that this study will assist machinists in the process design of machining operations for the development of products with good surface integrity.**

***Index Terms*—surface roughness, surface finish, cutting operation, tool steel**

I. Introduction

A hardened 2379 tool steel (TS) is known as a difficult-to-machine material and it is mostly used in the production of press tools, extrusion dies and die-castings. Some of properties of the material are high shock and thermal fatigue resistance, high temperature strength, and that their toughness, ductility and dimensional stability are hardly affected during hardening [1]. The difficulty in machining this material often results in surface roughness and dimensional inaccuracies. This can affect the quality and usefulness of the final product. Furthermore, the lesser the machinability of the material, the less sustainable the machining process becomes in term of material conservation, cost and time effectiveness, energy utilization and environmental friendliness. This is due to the fact that the amount of scraps generated or materials to be reworked will increase with reduction in the machinability of a material. This challenge will reduce the cost and time effectiveness of the machining process. In addition, the energy consumption may increase with reduction in the machinability of the material thus making the machining process costly and less environmentally friendly [2]. The energy consumption during machining operations can also be significantly influenced by the variation in the range of the process parameters [3-5]. In order to achieve effective material conservation, cost and time effectiveness, energy utilization and environmental friendliness during machining process, there is a need for effective process design, which will encompass the identification of the optimum cutting conditions that will ensure that the cutting and functional requirements are met [6-8]. Prominent out of the cutting requirement is surface finish. This is to ensure that the material is machined to the required surface finish and dimensional accuracy. The quality of a machined surface is very important since it is partly a function of the surface finish of the material, and the best surface finish is achievable at low measured surface roughness. Hence, the surface finish of a material is a contributing factor towards the quality of a machined part and this factor is usually influenced by the cutting speed, depth of cut and feed rate [9]. The prediction of surface roughness during machining operations has not yet yielded satisfying results, and to address this, Liu *et al.* [10] investigated the surface roughness using energy consumption concept to come up with alternative solutions. During the machining operation of hardened 2379 tools steel, there is high tendency for an increase in tool wear rate, and as a result, the use of frequent cooling can reduce the heat generated between the material and the cutting tool.

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This is to improve the surface finish of the machined material workpiece.

Arizmedi and Jiménez [11] modelled and analysed the surface topography generated in face milling operations. The authors concluded that the surface topography is affected by the runout of the inserts.

This study investigates the surface roughness of a hardened 2379 TS for face milling operation under soluble oil and air-cooling methods. The study is limited to the measurement of the surface roughness along the cutting direction only, which is in the x-axis, since this is the area predominantly under the significant influence of the cutting force.

During a machining operation, the Design of Experiment (DoE) approach have been widely employed for the determination of the optimum combination of process parameters that would enhance optimum cutting performance [12]. The Response Surface Methodology (RSM) and the Taguchi method are DoE techniques that can be used for the determination of surface roughness of a material [10, 13]. RSM can be employed for identifying the optimum range of process parameters during machining operations and can also be used for obtaining mathematical models for the correlation of independent process parameters as a function of the measured response most especially for large number of experimental trials [14]. On the other hand, the Taguchi approach is a technique, which can be applied for the determination of the optimum process conditions, and it is mostly employed in manufacturing field for engineering analysis. The approach is suitable for smaller number of experimental trials; hence, it is cost and time effective without sacrificing the costs of product development [15]. The limited number of work piece materials, which poise a limitation on the number of experimental trials, necessitates the use of the Taguchi approach in this study. There is still a dearth of information regarding the range of process conditions for effective machinability of hardened 2379 tools steel. Hence, this study contributes to the understanding of the optimum range of process conditions for effective face milling of hardened 2379 tools steel. The succeeding section presents the materials and methods employed, results obtained and discussion as well as conclusion and recommendations.

II. Materials & Methods

A. Physical Experiment

A 5-axis CNC milling machine, Deckel Maho DMU80 monoBLOCK was used to carry out the face milling experiments. The experiments were conducted at the Institute for Advanced Tooling (I. A. T.), Tshwane University of Technology (TUT) in Soshanguve South Campus. An indexable SANDVIK cutting tool with diameter 16 mm, carrying 2 cutting inserts R390-11 T3 08M-PM of grade 1010 for the machining process of 2739 TS workpiece which had dimensions of 50 x 16 mm, hardened at 55-58 HRC were employed. The workpiece was securely clamped in a hydraulic vice during machining operation and face milling operation was performed by an application of cooling method using both air and soluble oil at various cutting speeds, feed rates and depth of cut, which were selected within the recommended range specified by the cutting tool manufacturer (SANDVIK, 2020). New cutting inserts were used for every experimental cutting trial in order to achieve accurate results. The cutting operation was performed on a 50 mm long surface of the workpiece material under soluble oil and air-cooling conditions. Fig. 1 shows the workpiece (hardened 2379 tools steel) and the indexable SANDVIK cutting tool with inserts R390-11 T3 08M-PM while Fig. 2 presents the experimental set up for the physical experimentations.

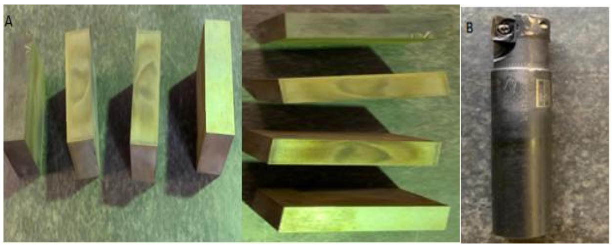

Figure 1. The workpiece and the cutting tool with inserts.

Figure 2. The physical experimental set up.

The Mitutoyo SJ-10 surface roughness tester (Fig. 3) was used to measure the surface roughness (R_a) observed during the machining operations, and the surface roughness measurements were taken along the cutting direction which was the x-axis direction.

Figure 3. The Mitutoyo SJ-10 surface roughness tester.Numerical Experiment

The Taguchi L4 orthogonal array approach was employed for the numerical analysis in order to be able to determine the feasible process parameters for the determination of the surface roughness of a hardened 2379 TS material during milling operation. The choice of the Taguchi approach stem from the need to achieve cost and time effectiveness during the machining operation due to the possibility of limited experimental trials [16-17]. Tables I and II present the build information as well as the design matrix of the factors (process parameters) considered. Three parameters were considered namely: cutting speed (ranges from a minimum value of 115 m/min to a maximum value of 125 m/min), feed per tooth (ranges from a minimum value 0.08 mm to a maximum value of 0.2 mm) and depth of cut (ranges from a minimum value of 0.25 mm to a maximum value of 0.5 mm). The choice of the three process parameters was based on a related work carried out which highlighted the cutting speed, feed per tooth and depth of cut as some of the major process parameters which can significantly influence the degree of surface roughness [18]. Table III lists the parameters used during the cutting operation while Tables IV and V present the summary of the experimental response under the air-cooling and soluble oil cooling conditions respectively using the 3FI model. The numerical experimentation was carried out in the Design Expert environment version 11.1.2.0, to determine the feasible combination of the process parameters that will produce minimal surface roughness under the air cooling and soluble oi l cooling conditions. The numerical experimentation produced a total of four experimental trials whose responses (surface roughness) was determined via physical experimentations at a build time of 2.00 ms. Comparative analysis was carried out between the results obtained numerically and physically in order to determine the suitability of the numerical models for predictive purpose.

TABLE I. BUILD INFORMATION FOR THE TAGUCHI TECHNIQUE.

File version	11.1.2.0		
Study type	Factorial	Subtype	Randomized
Design type	Taguchi OA	Runs	4
Design model	Main effects	Blocks	No of Blocks
Centre points	0	Build time (ms)	2.00

TABLE II. DESIGN MATRIX FOR THE PROCESS PARAMETERS.

Factor	Name	Unit	Type	Minimum	Maximum	Level
A	Cutting Speed	m/min	Categoric	115	125	2
B	Feed per tooth	mm	Categoric	0.08	0.2	2
C	Depth of cut	mm	Categoric	0.25	0.5	2

TABLE III. CUTIING PARAMETERS.

Runs	Cutting speed (m/min)	Feed per tooth (mm)	Depth of cut (mm)
1.	115	0.08	0.25
2.	125	0.2	0.25
3.	125	0.08	0.5
4.	115	0.2	0.5

TABLE IV. THE SUMMARY OF THE EXPERIMENTAL RESPONSE (AIR COOLING).

Response	Unit	Obs.	Analysis	Min.	Max.	Mean	Std. Dev.	Ratio	Process Order
Surface roughness	μm	4	Factorial	0.34	0.76	0.6100	0.1857	2.24	3FI

TABLE V. THE SUMMARY OF THE EXPERIMENTAL RESPONSE (SOLUBLE OIL COOLING)

Response	Unit	Obs.	Analysis	Min.	Max.	Mean	Std. Dev.	Ratio	Process Order
Surface roughness	μm	4	Factorial	0.25	0.65	0.4800	0.1869	2.60	3FI

III. RESULTS AND DISCUSSION

The Analysis of variance (ANOVA) is one of the indicators of a well-developed model for the prediction of the surface roughness. The summary of the ANOVA for the cutting operation under the air cooling and soluble oil cooling conditions are presented in Tables VI and VII respectively.

TABLE VI. ANOVA (AIR-COOLING).

Source	Sum of Squares	df	Mean Square
Model	0.1034	3	0.0345
A-Cutting speed	0.0144	1	0.0144
B-Feed per tooth	0.0529	1	0.0529
C-Depth of cut	0.0361	1	0.0361
Pure Error	0.0000	0	
Cor. Total	0.1034	3	

TABLE VII. ANOVA (SOLUBLE OIL COOLING).

Source	Sum of Squares	df	Mean Square	F-value	P-value
Model	0.0961	1	0.0961	16.43	0.0558
B-Feed per tooth	0.0961	1	0.0961	16.43	0.0558
Residual	0.0117	2	0.0059		
Cor Total	0.1078	3			

From Table VII, the Model F-value of 16.43 suggests that 5.58% chances are due to noise. Although the P-values is slightly above 0.05, it can be judged as moderately significant. Once values are above 0.1 the model becomes insignificant, and once they become many, a model reduction should be employed to improve the model. The statistical analysis of the model developed for cutting operation under the soluble oil cooling condition is presented in Table VIII. The value of the R squared (0.8915), and adjusted Predicted R^2 (0.8372) were close to 1 and their difference were found to be within the range of 0.2. Although the magnitude of the Predicted($\boldsymbol{R^2}$) was found to be 0.5659 which was significantly lower than 1. The magnitude of the Predicted($\boldsymbol{R^2}$) can be made closer to 1 by increasing the number of experimental runs.

Also, the adequate precision measures the S/N ratio to 5.7319 is desirable since it is greater than 4. Furthermore, the small magnitude of the value of standard deviation also lends credence to the fact that the developed model is suitable for predictive purpose. Therefore, this model can be used for prediction within the design space.

TABLE VIII. STATISTICAL ANALYSIS OF THE MODEL (SOLUBLE OIL COOLING).

Statistics	Value
Std. Dev	0.0765
Mean	0.4800
C. V. (%)	15.930
R squared ($\boldsymbol{R^2}$)	0.8915
Adjusted ($\boldsymbol{R^2}$)	0.8372
Predicted ($\boldsymbol{R^2}$)	0.5659
Adeq. Precision	5.7319

The surface roughness model as a function of the independent process parameters under the air cooling and soluble oil cooling conditions are presented in (1) and (2) respectively.

$$SR = +0.6100 - 0.0600A + 0.1150B - 0.0950C \quad (1)$$

$$SR = +0.4800 + 0.1550B \quad (2)$$

Where: A is the cutting speed (m/min), B is the feed per tooth (mm), and C is the depth of cut (mm).

Equations 1 and 2 can be employed for the prediction of surface roughness under similar cutting and process conditions.

The surface roughness measurement was conducted twice for each of the experimental trials and the average of the results obtained was taken as the average surface roughness for each of the trials. The replication of the surface roughness measurement was to ensure that the error in the magnitude of surface roughness is minimised. Table IX presents the average surface roughness obtained via physical experimentations for the various combination of the process parameters. The comparative analysis of the results obtained between the actual values of surface roughness obtained via the physical experimentations and the predicted values of the models under the air-cooling and soluble oil cooling conditions is presented in Table X. The minimal magnitude of the errors obtained (which is the difference between the values of the average and predicted surface roughness obtained also indicate that the model is suitable for the predictive purpose. By implication, it means the magnitude of the surface roughness obtained can be achieved using the feasible combinations of the process parameters obtained from the numerical experimentation.

TABLE IX. AVERAGE SURFACE ROUGHNESS OBTAINED FROM THE PHYSICAL EXPERIMENTATIONS.

Runs	Cutting speed (m/min)	Feed per tooth (mm)	Depth of cut (mm)	Average Surface roughness ($\boldsymbol{\mu}$m) (Air cooling)	Average Surface roughness ($\boldsymbol{\mu}$m) (Soluble oil-cooling)
1.	115	0.08	0.25	0.5550	0.4000
2.	125	0.2	0.25	0.7850	0.6500
3.	125	0.08	0.5	0.4350	0.2500
4.	115	0.2	0.5	0.6650	0.6200

TABLE X. COMPARATIVE ANALYSIS OF THE ACTUAL AND PREDICTED VALUES OF SURFACE ROUGHNESS.

Runs	Average Surface roughness ($\boldsymbol{\mu}$m) (Air cooling)	Predicted Surface roughness ($\boldsymbol{\mu}$m) (Air cooling)	Error	Average Surface roughness ($\boldsymbol{\mu}$m) (Soluble oil-cooling)	Predicted Surface roughness ($\boldsymbol{\mu}$m) (Air cooling)	Error
1.	0.5550	0.5278	0.0272	0.4000	0.3250	0.0750
2.	0.7850	0.7608	0.0842	0.6500	0.6350	0.0150
3.	0.4350	0.4687	0.0337	0.2500	0.3250	0.0750
4.	0.6650	0.6745	0.0095	0.6200	0.6350	0.0150

From Table IX, the results obtained indicate that the cutting operation under the soluble oil cutting condition produced a better finish when compared with the cutting operation under the air cooling condition. The development of built-up of edges was observed under the air cooling operation compared to the soluble oil cooling condition. The optimum combination of the process parameters which produced the least surface roughness under the air cooling condition are surface roughness (0.4350 $\boldsymbol{\mu}$m), cutting speed (125 m/min), feed per tooth (0.08 mm) and depth of cut (0.5 mm). On the other hand, the optimum combination of the process parameters which produced the least surface roughness under the soluble oil cooling condition are surface roughness (0.2500 $\boldsymbol{\mu}$m), cutting speed (125 m/min), feed per tooth (0.08 mm) and depth of cut (0.5 mm). The results indicate that the surface roughness values under the soluble cooling condition is slightly lower than that of the air cooling condition. This is an indication that for this experiment, the soluble oil cooling condition is more efficient than the air cooling condition. More experimentations can be carried out to validate this findings. The model developed under the different cutting conditions (1 and 2) were employed for the prediction of surface roughness. The comparative analysis of the results obtained between the actual values of surface roughness obtained via the physical experimentations and the predicted values of the models under the air-cooling and soluble oil cooling conditions is presented in Table X.

Fig. 4 shows the comparative analysis of the actual and predicted values of surface roughness for the air cooling while Fig. 5 shows the error bar generated from the comparative analysis. The similarity in the data pattern of both plots indicate the closeness of the actual and predicted values of surface roughness. The negligible value of the standard deviation and the short length of the error bars shown in Fig. 5 further lends credence to the fact that there is significant agreement between the predicted and actual values. Fig. 6 shows the comparative analysis of the actual and predicted values of surface roughness for the soluble air cooling while Fig. 7 shows the error bar generated from the comparative analysis. The similarity in the data pattern of both plots indicate the closeness of the actual and predicted values of surface roughness. The negligible value of the standard deviation and the short length of the error bars shown in Fig. 7 further lends credence to the fact that there is significant agreement between the predicted and actual values.

This is an indication that the developed model is suitable for predictive purpose. Fig. 8 shows the comparative analysis of the magnitude of the surface roughness obtained under the air-cooling and soluble oil cooling condition. Fig.8 indicates that the cutting operation under the soluble oil cooling condition produced better surface finish (lower surface roughness) as opposed to the cutting operation under the air cooling condition. This is because the soluble oil washes away the chips that might come in contact with the cutting tool and the workpiece material while with air cooling some of the chips were observed to stick to the workpiece material resulting in the formation of built-up edges.

In essence, the chances for built up edges is lower under the soluble oil cooling than under the air cooling condition. The higher the chances for the built up edges the lower the surface finish and vice versa. The results obtained indicated that the feed per tooth has a positive effect on the surface roughness while the depth of cut and cutting speed has a negative effect. This implies that an increase in the magnitude of the feed per tooth brings about significant reduction in magnitude of surface roughness and vice versa. On the other hand, increase in the magnitude of the depth and cutting speed result in increase in the magnitude of the surface roughness. The reasons for the positive and negative effects of the process parameters on the magnitude of surface roughness depends on a number of factors. For instance, the feed per tooth measures the amount of material that should be removed by each tooth of the cutter during its revolution and advancement into the workpiece. As the cutting tool engages the workpiece material, each teeth of the cutter advances into the workpiece an equal amount producing chips of equal thickness. The higher the magnitude of the feed per tooth, the more chips of equal thickness are produced and the lower the magnitude of surface roughness and vice versa. For the depth of cut, an increase in the magnitude of the depth of cut will bring about an increase in the chip load and tendency for the development of built up edges. The magnitude of the surface roughness increases with an increase in the chip load and formation of built up edges. The cutting speed measures the relative velocity between the cutting tool and the workpiece surface. The higher the cutting speed, the higher the surface temperature and vice versa. Unless a system of effective cooling is put in place, an increase cutting speed may promote increase in the surface temperature with the development of residual stresses, which may promote surface roughness. The optimization of surface roughness is aimed at reducing its magnitude. Keeping the process parameters (cutting speed, feed per tooth and depth of cut) in range, six optimal solutions were obtained for the cutting operation under the air-cooling condition. Out of these six solutions, the solution which has the least surface roughness whose desirability equals to 1 for the air cooling condition are as follow: surface roughness (0.430 $\boldsymbol{\mu}$m), cutting speed (125 m/min), feed per tooth (0.08 mm) and depth of cut (0.5 mm).

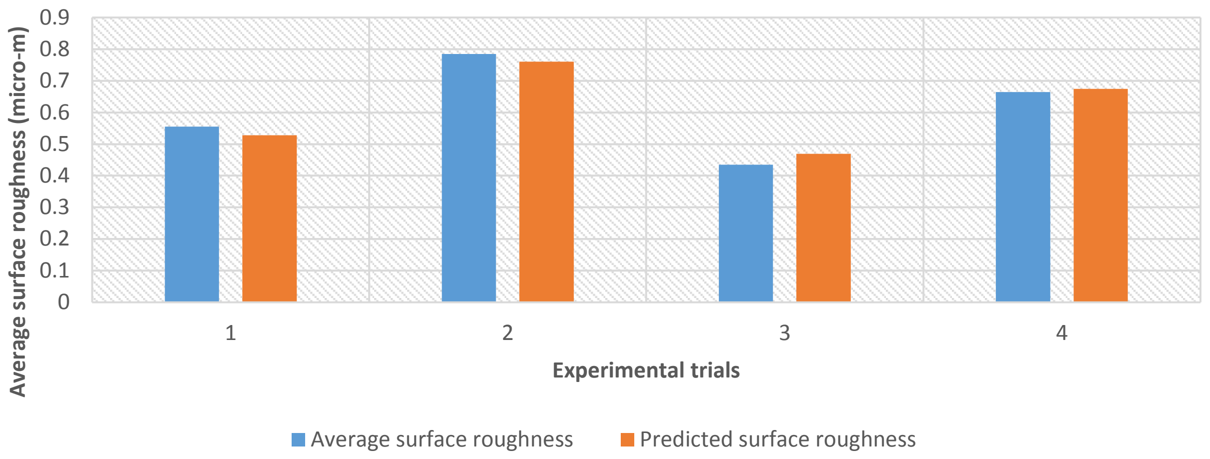

Figure 4. Comparative analysis of the actual and predicted values of surface roughness (air-cooling).

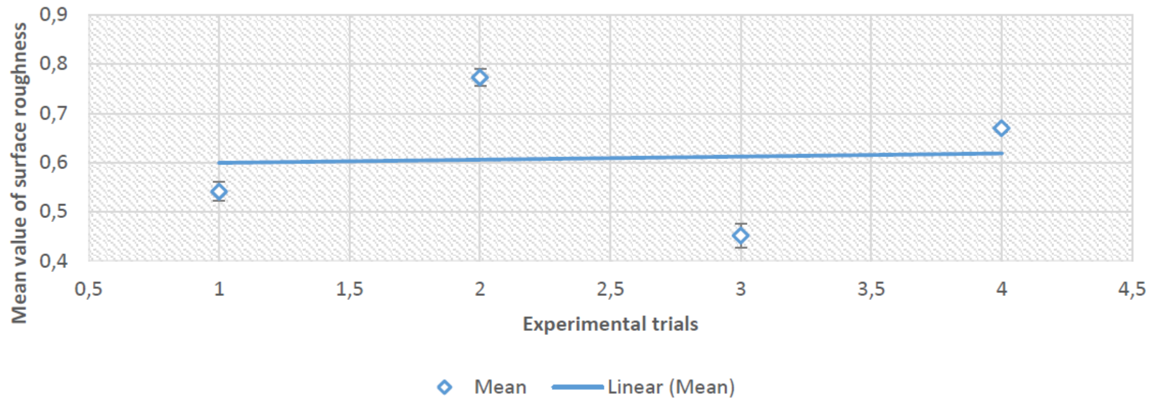

Figure 5. Error bar for the actual and predicted values of surface roughness (air-cooling).

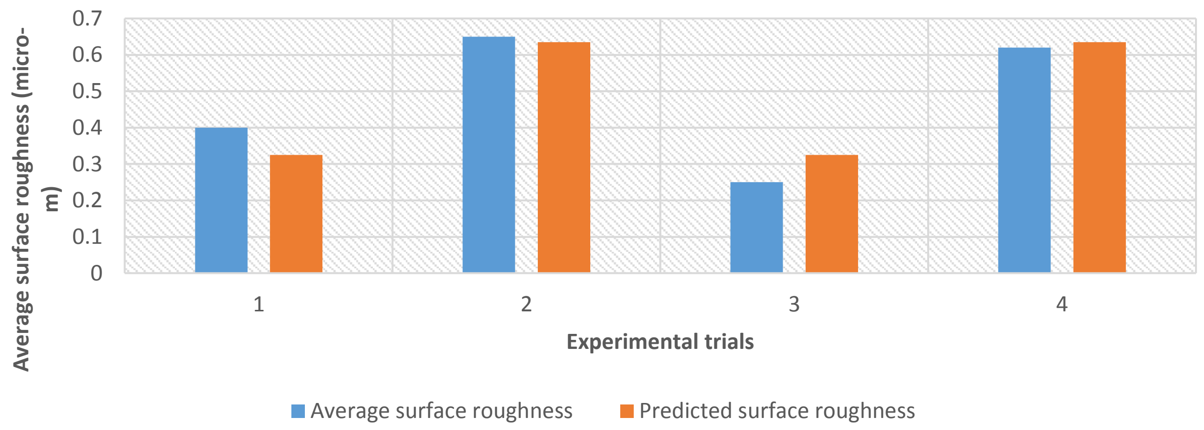

Figure 6. Comparative analysis of the actual and predicted values of surface roughness (soluble oil cooling).

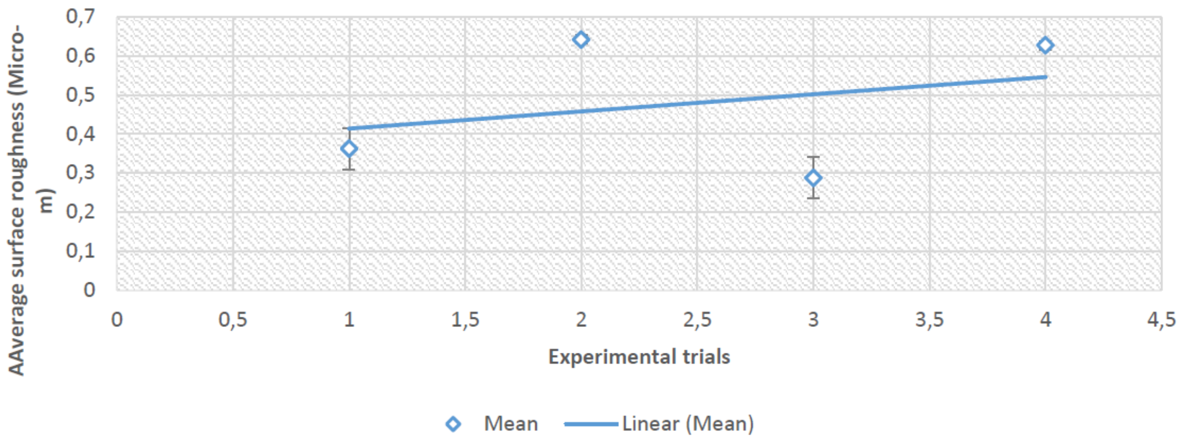

Figure 7. Error bar for the actual and predicted values of surface roughness (Soluble oil cooling).

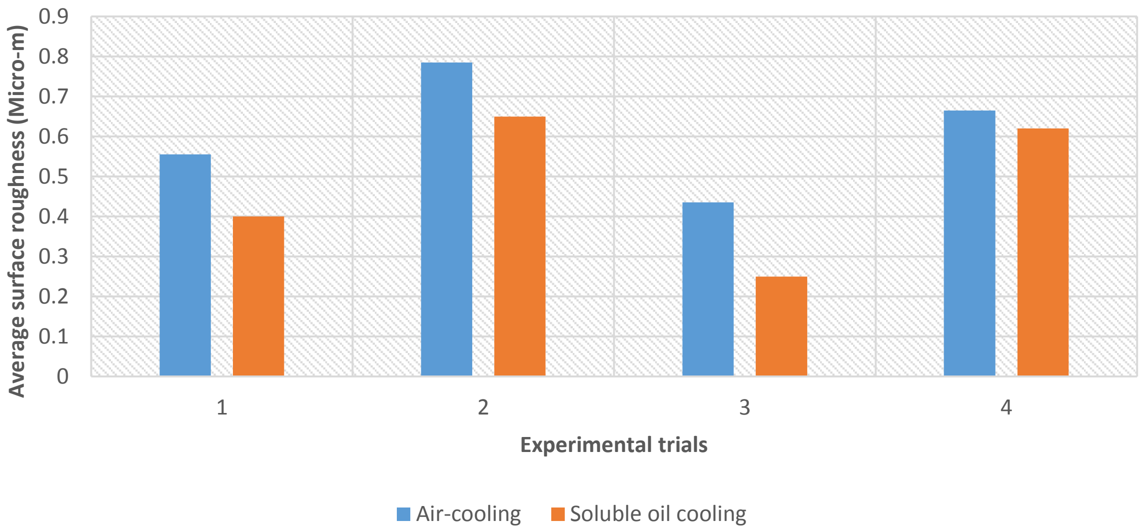

Figure 8. Comparative analysis of the surface roughness values under different cooling conditions.

The optimization produced two feasible solutions whose desirability equals to 1. Out of these two solutions, the solution, which has the least surface roughness whose desirability, equals to 1 for the soluble oil cooling condition are as follow: surface roughness (0.200 μm), cutting speed (125 m/min), feed per tooth (0.08 mm) and depth of cut (0.5 mm).

IV. Conclusion

The aim of this study was to investigate the machinability of a hardened 2379 TS under air and soluble oil cooling methods using R390 11 T3 08M PM 1010 SANDVIK cutting inserts. The face milling operation was performed on the material and the surface roughness were measured under the different cooling conditions. The results of those two cooling methods were compared against each other and conclusion drawn was that soluble oil cooling gives better surface finish than air cooling method. A better surface finish were obtained at high cutting speed, low cutting feed rates and low depth of cuts. The statistical analyses of the results obtained via the numerical and physical experimentations were used to obtained two predictive models which correlates the surface roughness as a function of the independent process parameters (cutting speed, depth of cut and feed per tooth) under the air cooling and soluble oil cooling conditions. The higher the magnitude of the cutting parameter, higher the tendency for poor surface finish and vice versa.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The work is a product of the collective efforts of all the authors.

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