Optimization of turning parameters for surface roughness

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***Abstract*— In this paper, Taguchi Design is used to identify the optimal combination of turning parameters to minimize the surface roughness. Turning experiments are carried out according to Taguchi orthogonal array L_9 for various combinations of four parameters: cutting speed, feed rate, depth of cut and nose radius. For each experiment run, the surface roughness *Ra* is measured, recorded and analyzed using Taguchi S/N ratios. To confirm the effectiveness of the Taguchi optimization, confirmation test and regression model are used.**

Keywords—Optimization; Taguchi Design of Experiments; Regression model; surface roughness; turning.

I. Introduction

Turning is one of the widely used machining processes in industries. In turning, a single-point cutting tool removes material from the surface of a rotating cylindrical work piece. The cutting tool is fed linearly in a direction parallel to the axis of rotation. Turning is carried out on a lathe that provides the power to turn the work piece at a given rotational speed and to feed the cutting tool at a specified rate and depth of cut. Therefore, three cutting parameters, i.e. cutting speed, feed rate and depth of cut need to be determined in a turning operation. Fig. 1 shows a basic turning operation.

In turning, the important task is to select cutting parameters in order to achieve the highest cutting performance such as surface roughness, material removal rate, tool wear and power consumption. Habitually, conducting experiments or using a handbook can determine the required cutting parameters. Unfortunately, these means don't lead to optimal cutting performance for a particular machine tool and environment.

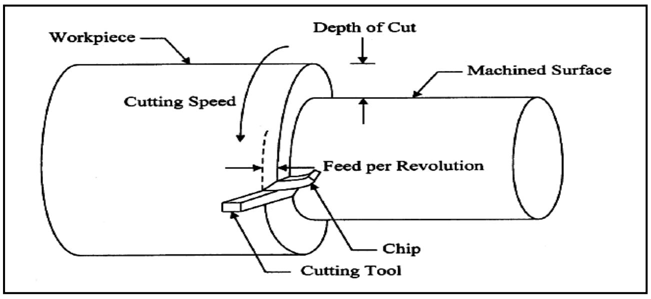

Fig. 1. Basic turning operation.

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Surface roughness remains the main indicator of machined component quality. A low surface roughness improves the tribological properties, fatigue strength, corrosion resistance and esthetic appeal of the product [1].

Literature is very rich in terms of turning operation owing to its importance in metal cutting. The three important process parameters in this research are speed, feed rate and depth of cut. Surface roughness of a turned work piece is dependent on these process parameters and also on tool geometry: nose radius, rake angle, side cutting edge angle and cutting edge. It also depends on the several other exogenous factors such as: work piece and tool material combination and their mechanical properties, quality and type of the machine tool used, auxiliary tooling, lubricant used and vibrations between the work piece, machine tool and cutting tool [2-8].

Several studies proposed optimization of cutting parameters for surface roughness and other cutting performance [9-11].

The influence of process parameters like cutting speed, feed rate and depth of cut on flank wear and surface roughness in turning was studied in [9]. The experiments were carried out based on Taguchi orthogonal array. The research provided optimized parameter solution with the utilization of uncoated tungsten carbide inserts during machining *Al/SiCp* metal matrix composite under dry cutting conditions.

The study conducted in [10] discussed an application of the Taguchi design to investigate the effects of process parameters on the metal removal rate value, in the electrochemical machining of *LM6 Al/5%SiC* composites. It also provided the optimal values of voltage, feed rate and electrolyte concentration that lead to the maximum metal removal rate.

The effects of cutting tool, cutting speed, feed rate and drill bit angle on the surface roughness were investigated by [11]. This study concerned the drilling of Waspaloy superalloy. The experiments were carried out according to Taguchi design. The optimum levels of control factors for minimum surface roughness were defined by using S/N ratios.

Unfortunately, the previous studies included just the three major parameters (cutting speed, feed rate and depth of cut) and neglect an important one: tool nose radius, which has a considerable effect on surface roughness. Moreover, a large number of turning experiments is required to develop mathematical models. So, this mean is very costly in terms of time and materials. In this study, an alternative optimization approach, based on the Taguchi Design of Experiments (DoE), is used to determine the optimal combination of parameters.

Taguchi DoE is a powerful tool for the design of high quality systems [12]. It provides a simple, efficient and systematic approach to optimize designs for performance, quality, and cost. Taguchi proposed a set of orthogonal arrays to investigate the effect of parameters on specific quality characteristics and determine the optimum parameters combination. These arrays use a small number of experiments which save time and resources. However, these arrays don't test all variables combinations and interactions which could make their risk of error very large. Then, these designs should not be used when all relationships between all variables are needed.

In our study, Taguchi DoE is adopted to identify the optimal combination of turning parameters (cutting speed, feed rate, depth of cut and nose radius) to optimize surface roughness. First, we present the Taguchi Design. Next, we describe the experimental system and results of optimization. Finally, the paper concludes with conclusion and future work.

II. METHODS

In our optimization of surface roughness, we included four cutting parameters:

- Cutting speed *V*;
- Feed rate *f*;
- Depth of cut *a*;
- Nose radius *r*.

A. Modeling of surface roughness

The surface roughness average *Ra* was taken as a parameter, defined on the basis of the ISO 4287 Norm [13] as the arithmetic mean of the deviations of the roughness profile from the central line l_m along the measurement. This definition is set out in (1), where *y(x)* is the profile value of the roughness profile and *L* is the evaluation length.
Characteristics of roughness profile are shown in Fig. 2:

$$Ra = 1/L \int |y(x)| dx \quad (1)$$

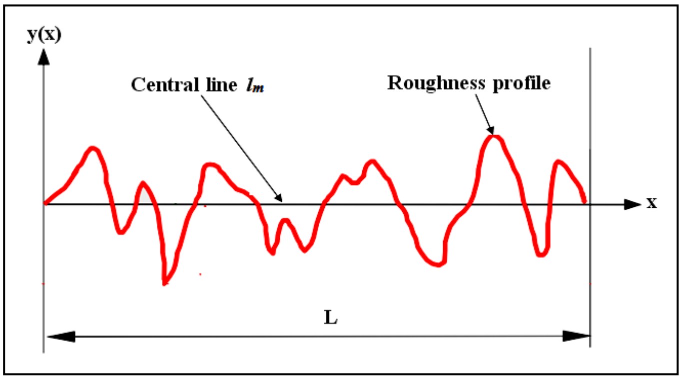

Fig. 2. Roughness profile characteristics.

Equation (2) represents an exponential empirical model for surface roughness that was suggested in [3].

$$Ra = C.V^n.f^m.a^p \quad (2)$$

Where *C*, *n*, *m* and *p* are indexes which describe the empirical model.

A widely known empirical model to estimate the average surface roughness is given in (3) [14, 15]:

$$Ra = f^2/32r \quad (3)$$

B. Description of Taguchi Design

The Full Factorial Design with four factors and three levels needs *81* experiments to carry out. This high number takes time and requires a very high cost. Therefore, Taguchi proposed a unique design of orthogonal array to investigate the full parameter with a small number of experimental trials. This design reduces the experimental process, minimizes the effects of factors that cannot be controlled and identifies significant factors quickly [12].

The Taguchi's quality loss function approach was performed to calculate the deviation between the experimental values and the optimal values. This function is further regenerated into a Signal-to-Noise (S/N) ratio and the parameters are evaluated based on the S/N ratio.

The S/N ratio indications can be separated into three groups, called performance characteristics:

- The Smaller-the-Better,
- The Larger-the-Better,
- The Nominal-the-Better.

Regardless of the type of the performance characteristic, a large S/N ratio means it is close to good quality. Then, a higher value of the S/N ratio is desirable.

Generally, the steps applied for Taguchi optimization are as following:

- Select parameters and their levels;
- Select Taguchi orthogonal array;
- Conduct experiments and measure the response to optimize;
- Analyze results by using Signal-to-Noise ratio;
- Identify optimum levels of parameters;
- Confirm the effectiveness of optimization with a confirmation test.

In our study, four parameters with three levels each were considered which correspond to Taguchi L_9 orthogonal array.

C. Full Factorial Design and Multiple Regression Model

Full Factorial Design is an experiment whose design consists of two or more factors, each with discrete possible levels, and whose experimental units take on all possible combinations of these levels across all such factors. This factorial design allows his user to study the effect of each factor on the response variable, as well as the effects of interactions of factors on the response variable [16].

Most of factorial experiments use only two levels for each factor. The number of combinations is denoted by 2^n, where n is the number of independent variables. If the number of combinations in a full factorial design is too high to be logistically executed, a fractional factorial design may be done, in which some of the possible combinations (usually at least half) are omitted.

Multiple Regression is a statistical method that allows us to determine the correlation between a continuous dependent variable and two or more continuous or discrete independent variables. It can be used for a variety of purposes such as analyzing of experimental, ordinal, or categorical data [17].

In our study, the purpose of using the Full Factorial Design and Regression Model was to confirm the effectiveness of Taguchi optimization. We used a design of four factors with two levels each and we developed a regression model with interactions between factors.

III. EXPERIMENTAL SYSTEM

A. Material of work piece and cutting tool

For the work pieces, AISI 1042 Steel (58.55 HRC) in the form of round bars with *50 mm* diameter and *40 mm* of cutting length are used for turning operations. This type of steel is chosen due to its high machinability and commercial availability. The chemical composition of this material is as following:

- Carbon *C*: 0.40 - 0.47 %,
- Iron *Fe*: 98.5 - 99.0 %,
- Manganese *Mn*: 0.6 - 0.9 %,
- Phosphorus *P*: 0 - 0.04 %,
- Sulfur *S*: 0 - 0.05 %.

We used the same material for all work pieces to guaranty the same experimental conditions for all experiments. Indeed, from a type of steel to another, the physico-chemistry composition changes and can induce variability in the experimental process.

For the cutting tool, standard carbide tool inserts CNMG120402, CNMG120404 and CNMG120408 were used for turning experiments with nose radius of *0.2 mm*, *0.4 mm* and *0.8 mm*, respectively.

B. Cutting conditions and measurement

Turning experiments were conducted on a Computer Numerical Controlled (CNC) Lathe, in the Laboratory of Mechanical Manufacturing of ENSAM, Moulay Ismail University, Meknes, Morocco. Photographs of CNC Lathe and experimental system are shown in Fig. 3 and Fig. 4, respectively.

Fig. 3. Photograph of the CNC Lathe.

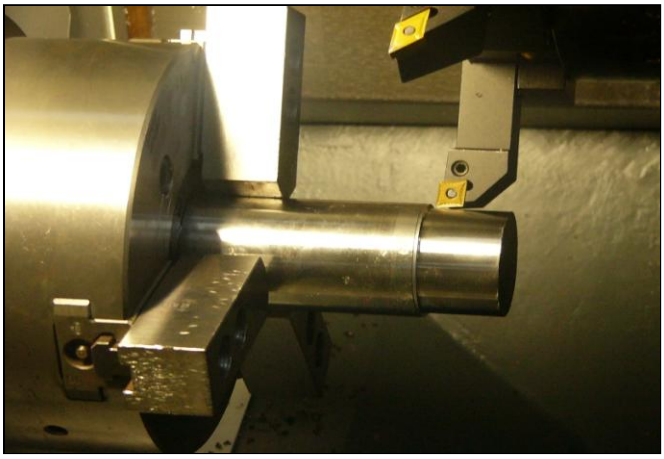

Fig. 4. Experimental system.

For each parameter, three levels were selected and their low-medium-high levels are shown in Table I. The selection of levels of machining parameters took into consideration the material of both work piece and cutting tool. The experiments were conducted without lubricant.

The work surface was characterized with roughness parameters as the arithmetic surface roughness average *Ra*. After each turning operation, *Ra* was measured by a Roughness Tester. The measurement is shown in Fig. 5.

TABLE I. CUTTING PARAMETERS AND THEIR LEVELS.

Parameters		**Levels**		
		Low	***Medium***	***High***
V	Cutting speed (m/min)	100	150	200
f	Feed rate (mm/rev)	0.1	0.15	0.2
a	Depth of cut (mm)	1	1.5	2
r	Nose radius (mm)	0.2	0.4	0.8

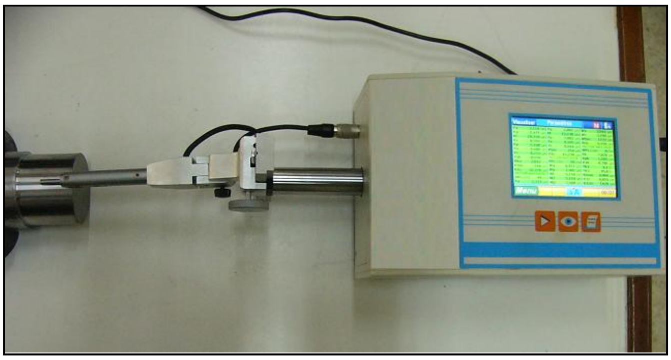

Fig. 5. Measurement of surface roughness by Roughness Tester.

The measurement was repeated thrice at different locations for each work piece and average value is reported. Details of setting parameters of measure are as following:

- Cut-off length = 0.8 mm; Cut-off number = 5;
- Standard: ISO 4287; Speed = 1 mm/s.

C. Experimental data

In order to optimize the surface roughness, we used the L_9 Taguchi orthogonal array to conduct the experiments. Experimental combinations of the turning parameters and the measurement of surface roughness *Ra* are reported in Table II.

To confirm the effectiveness of Taguchi optimization, we used a full factorial design of the same parameters used in Taguchi optimization, but we were restricted to two levels (low and high). Then, *16* experiments were carried out to develop the regression model. This model will be used later to confirm the Taguchi optimization.

IV. RESULTS AND DISCUSSIONS

Experimental data was analyzed according to Taguchi Design by using Minitab 17, statistical analysis software widely exploited in many engineering optimizations.

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value for the output characteristic. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value.

TABLE II. EXPERIMENTAL DATA.

Run Order	V (m/min)	f (mm/rev)	a (mm)	r (mm)	Ra (µm)
1	100	0.10	1.0	0.2	3.575
2	100	0.15	1.5	0.4	1.212
3	100	0.20	2.0	0.8	1.301
4	150	0.10	1.5	0.8	1.894
5	150	0.15	2.0	0.2	0.993
6	150	0.20	1.0	0.4	1.654
7	200	0.10	2.0	0.4	0.618
8	200	0.15	1.0	0.8	0.713
9	200	0.20	1.5	0.2	1.483

First, Signal to Noise S/N ratios were determined by (4) with consideration of Lower-the-Better performance characteristic in terms of dB (decibel) [12]. We chose this characteristic because *Ra* value is requested to be low. The experimental values and their corresponding S/N ratios are listed in Table III.

$$S/N_{LB} = -10*\log (1/n \sum Ra_i^2) \quad (4)$$

Where *Ra* is the value of surface roughness for the i^{th} test in a run. In our case, n=1.

Next, the Mean S/N ratio at each level of cutting parameters was obtained by averaging at corresponding levels. For example: Mean S/N ratio for cutting speed *V* at the low level was calculated by averaging the S/N ratios for the experimental runs 1, 2 and 3, respectively. Similarly, the Mean S/N ratio for each level of other parameters can be computed.

Mean S/N ratios are presented in Table IV and their main effects plot are shown in Fig. 6.

Regardless of the type of the performance characteristic, a large S/N ratio means it is close to good quality. Then, a higher value of the S/N ratio is desirable.

From the Table IV and Fig. 6, optimal turning parameters values for surface roughness are highlighted and are as following:

- Cutting Speed *V*: 200 m/min;
- Feed rate *f*: 0.15 mm/rev;
- Depth of cut *a*: 2 mm;
- Nose radius *r*: 0.4 mm.

The confirmation test is the final step in verifying the optimal levels of parameters identified by Taguchi design. It is a crucial step and is highly recommended by Taguchi to verify the effectiveness of optimization.

In this study, a confirmation test was conducted by using the levels of the optimal parameters and we obtained:

$$Ra_{exp} = 2.15 \ \mu m.$$

TABLE III. EXPERIMENTAL RESULTS AND CORRESPONDING S/N RATIOS.

Run Order	Ra (µm)	S/N ratio (dB)
1	3.575	- 11.0647
2	1.212	- 1.6701
3	1.301	- 2.2855
4	1.894	- 5.5461
5	0.993	0.0581
6	1.654	- 4.3690
7	0.618	4.1755
8	0.713	2.9382
9	1.483	- 3.4209

TABLE IV. MEAN S/N RATIOS FOR SURFACE ROUGHNESS.

Levels	V	f	a	r
Low	-5.0068	-4.1451	-4.1652	-4.8092
Medium	-3.2856	**0.4421**	-3.5457	**-0.6212**
High	**1.2310**	-3.3585	**0.6494**	-1.6311
Delta	6.2377	4.5872	4.8145	4.1880
Rank	1	3	2	4

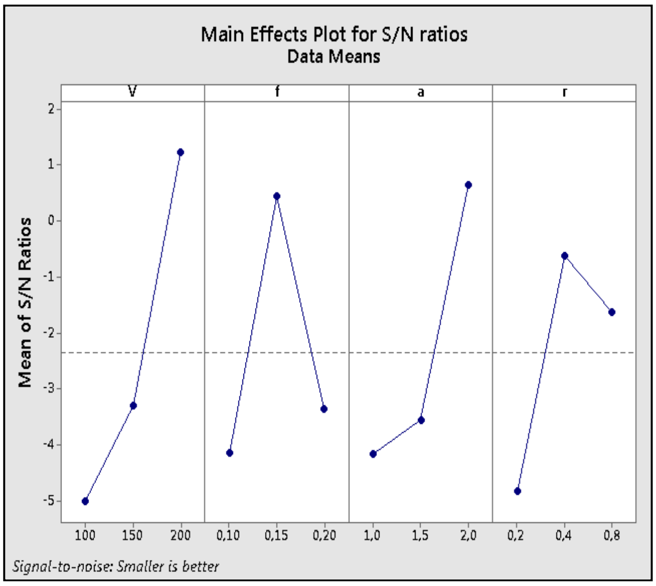

Fig. 6. Main Effects Plot for S/N ratios.

Compared to the nine previous experiments in the L_9 array, this value is not minimum, but it can be used for industrial applications which require this level of surface roughness.

This result is due to the orthogonality of Taguchi array which doesn't include interactions between parameters.

The empirical and widely used model [14, 15] given in (5) indicates that the effect of interaction between feed rate *f* and nose radius *r* is very important and cannot be neglected. A small value of *f* and a high value of *r* decrease significantly the surface roughness.

$$Ra = f^2/32r \quad (5)$$

In addition, we developed a regression model of the third order by using the full factorial design. *16* experiments were carried out and the developed model with interactions between parameters is given in (6):

$$Ra=10.34-56.1\mathbf{f}-4.77\mathbf{a}-18.35\mathbf{r}-0.1643\mathbf{V.f}+32.66\mathbf{f.a}+129.2\mathbf{f.r}+8.61\mathbf{a.r}+0.03054\mathbf{V.a.r}-67.22\mathbf{f.a.r} \quad (6)$$

This model has a great coefficient of determination of *99.55%* and an error of *0.07*. Errors between estimated and experimental values of surface roughness are represented in Fig. 7.

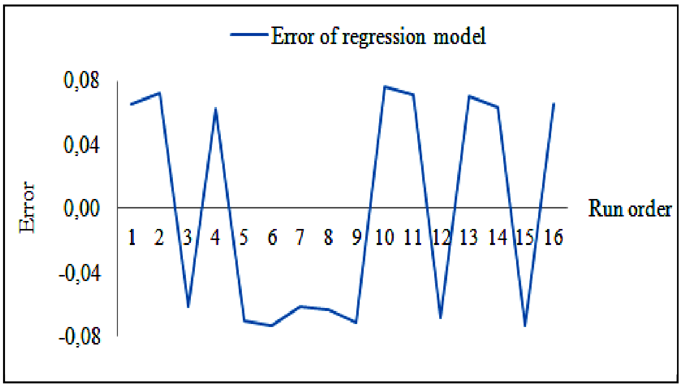

Fig. 7. Error of the developed regression model.

The low errors indicate that estimated values by the regression model are very close to those recorded experimentally.

These performances support the choice of this regression model to confirm the effects of interactions between parameters on surface roughness. Indeed, it reveals that the second order interaction (***f.r***) and the third order interaction (***f.a.r***) have the main effects on surface roughness.

V. CONCLUSION

Is this paper, Taguchi Design of Experiments was applied for turning parameters to obtain the optimal surface roughness.

For our optimization, we selected four turning parameters: Cutting speed, feed rate, depth of cut and nose radius. For each parameter, we selected three levels: low, medium and high.

Experiments were conducted using L_9 orthogonal array. For each experiment, surface roughness was measured, recorded and analyzed using Taguchi S/N ratios. These ratios were calculated with consideration of performance characteristic: Lower-the- Better, as surface roughness is requested to be low.

The optimum levels of parameters for minimizing the surface roughness were determined from the response table for Signal-to-Noise ratios. The best combination was obtained with:

- Cutting speed of *200 m/min*,
- Feed rate of *0.15 mm/rev*,
- Depth of cut of *2 mm*,
- Nose radius of *0.4 mm*.

To confirm the effectiveness of our optimization, we followed two ways:

- Confirmation experiment,
- Development of regression model with interactions between parameters.

Confirmation experiment revealed that Taguchi design cannot identify effectively the optimal parameters as the optimal turning parameters didn't lead to the minimal surface roughness. This result is due to the L_9 Taguchi orthogonal array, which doesn't include interactions between parameters.

To illustrate the effects of interactions between parameters, we developed a regression model of the third order. It had a great coefficient of determination and a low error, which allowed us to confirm that interactions between turning parameters affect significantly the surface roughness. Indeed, we found that the interaction between feed rate *f* and nose radius *r* had the major effect on surface roughness.

From these results, we concluded that it is crucial to consider the effects of interactions between turning parameters in optimization of surface roughness. This will be the objective of our future study, where optimization will be performed with other methods that include interactions between parameters.

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