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OPTIMIZATION OF CHEMICAL MACHINING CONDITIONS OF COLD WORKED STAINLESS STEEL 420 USING TAGUCHI METHOD

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ABSTRACT

Chemical machining has a considerable value in the solution of machining problems that are constantly arising due to the requirement for high surface finish of difficult to machine materials such as stainless steel which has a widespread application in industry in annealed and cold worked forms. The present work is aimed at utilizing of robust experimental design Taguchi method for optimization of chemical machining parameters. The influence of machining temperature, machining time, and previous cold working on surface finish of chemically machined stainless steel-420 samples. Taguchi experimental design concept, L'16 (3×4) mixed orthogonal array is used to determine the S/N ratio, analysis of variance, F- test to indicate the significant parameters affecting the surface finish, and to optimize the process parameters. Basing on the analyses of multiple regression method, mathematical predictive model had been designed and validated to select an optimum combination of the studied parameters. To achieve the objectives of the present work Datafit ver9, and Mtb14 softwares had been employed.

Alloy samples of (44.5×44.5×3mm) dimensions with (0, 20, 40, and 60%) cold rolled alloy samples were chemically machined at machining temperatures of (45, 50, 55, and 58°C) for a machining times of (2, 4, 6, and 8min.). The results show that previous cold working is the most significant parameter for the surface performance. Cold worked stainless steel 420 can be chemically machined in [H2O + HCl + HNO3 + HF + HCOOH] etchants in optimum conditions of 60% cold working at 45ºC for 2 min. Conformation tests verify the effectiveness of results of the designed predictive model with an error ranging between (4-12%).

Keywords: CHM, Cold Working, Optimization, Stainless Steel, Surface Roughness, Taguchi Method.

1. INTRODUCTION

The advancement of technology causes to the development and use of high properties materials. Widespread of engineering applications of such materials is restricted due to their poor machining characteristics despite excellent physical and mechanical properties. Many machined components require high surface finish and dimensional accuracy, complicated shape and special size which cannot be achieved by the conventional machining processes [1]. Moreover, the rise in temperature and the residual stresses generated in the workpiece due to traditional machining processes may not be acceptable. These requirements have led to the development of non- traditional machining processes, one of which is the chemical machining (CHM). This process is a precision contouring of metal into any size, shape or form without use of physical force, by a controlled chemical reaction. Material is removed by microscopic electrochemical cell action, as occurs in corrosion or chemical dissolution of a metal.

Chemical machining offers virtually unlimited scope for engineering and design ingenuity. To gain the most from its unique characteristics, it should be approached with the idea that this industrial tool can do jobs not practical or possible with any other metal working methods [2]. The performance of the chemical machining process is affected by several parameters, the more important of which are: the type of etchant solution and its concentration, the maskant and its application, machining temperature, machining time, and the previous cold working of the part to be machined. Such parameters have direct effect on the machining processes and on the characteristics of the machined parts concerning the machining rate, production tolerance, and particularly the surface finish. So, proper identification of an effective surface finishing process to achieve the required quality of surfaces represents a serious challenge to the user of the chemical machining.

Limited efforts have been directed towards improving the efficiency of the process. Fadaei Tehrani A. in [3] reported that increasing of machining temperature of stainless steel 304 causes an increase in its machining rate and a good surface finish can be achieved by adding triethanolamine to the etchant. David M. Allen in [4] showed that variations in etchant's specific gravity, machining temperature, and oxidation–reduction potential can affect the rate of etch with a change in etched dimensions and surface finish. Ho S. in [5] showed that the rate of metal removal is up to six times greater for nanocrystalline Ni than conventional polycrystalline Ni and shorter working times are needed. Yao Fua in [6] showed that increasing the cold work level (up to 60%) steadily decreased the corrosion resistance of the high nitrogen stainless steel in a 3.5% NaCl solution. Kurc A. in [7] found that cold rolled samples show a little lower resistance on corrosion in artificial sea water than material in delivery state. There appear to need more research contribution to develop modification of the CHM process to enhance its performance.

The objective of the present work is aimed at studying the effect of CHM parameters such as machining temperature, machining time, and the effect of previous cold working on the surface finish of stainless steel 420. Taguchi experimental design concept, L'16 (3×4) mixed orthogonal array is used to determine the S/N ratio, analyses of variance, F- test to indicate the significant parameters affecting the surface finish, and to optimize the process parameters. Basing on the analyses of multiple regression method, mathematical predictive model had been designed and validated to select an optimum combination of the studied parameters. To achieve the analyses of the present work Datafit ver9, and Mtb14 softwares had been employed.

2. MATERIALS USED IN THE PRESENT STUDY

A sheet (1000×1000×3 mm) of stainless steel 420 with a chemical composition of (0.09%C, 0.3%Si, 9.7%Mn, 15.66%Cr, 0.002%Mo, 0.6%Ni, 0.08%V, and Fe) was used in this work. To study the effect of previous cold working 20, 40, and 60% cold rolled samples had been prepared. All samples were cut to dimensions of (45×45mm).Depending on the used alloy, methylethylketone peroxide was selected to prepare the maskant [8]. The used etchant was a mixture of acids (H_2O + HCl + HNO_3 + HF + HCOOH) with concentrations in ml of (1500 + 106 + 83 + 9 + 82) as such chemical composition and concentration are effective to chemically machine a stainless steel alloy [3].

3. SAMPLES PREPARATION AND TESTS

Before coating with maskant material, the samples were cleaned from dirt, dust, fats, oils and organic compounds using alcohol (ethanol 98%). A specially designed glass mold was used for coating the samples. After pouring the polymeric masking material, the mold was kept in an oven at 80 ºC for 30 min for drying. One side (face) of a sample was left without coating, which represents the area to be machined. A hole of 2 mm diameter was drilled in each sample for the purpose of suspension in the etchant solution by using plastic tongs during the machining process. Fig.1 shows samples before and after the coating.

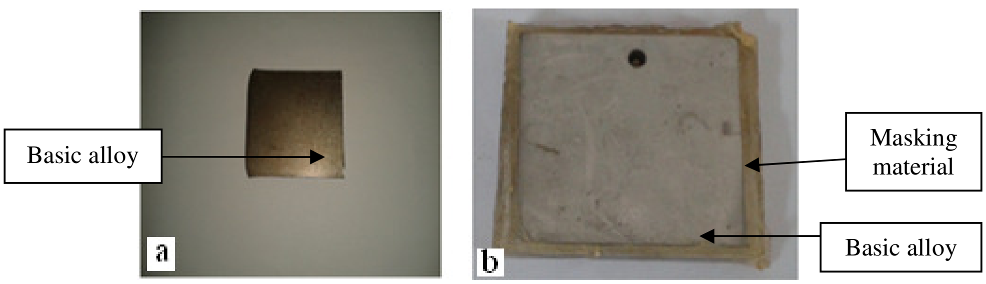


Figure (3): Specimens: (a) before coating; (b) after coating.

The machining process was achieved via magnetic stirrer thermostat which contains a thermostat to regulate the temperature of etchant during the machining operation and controller on velocity as shown in Fig.2.

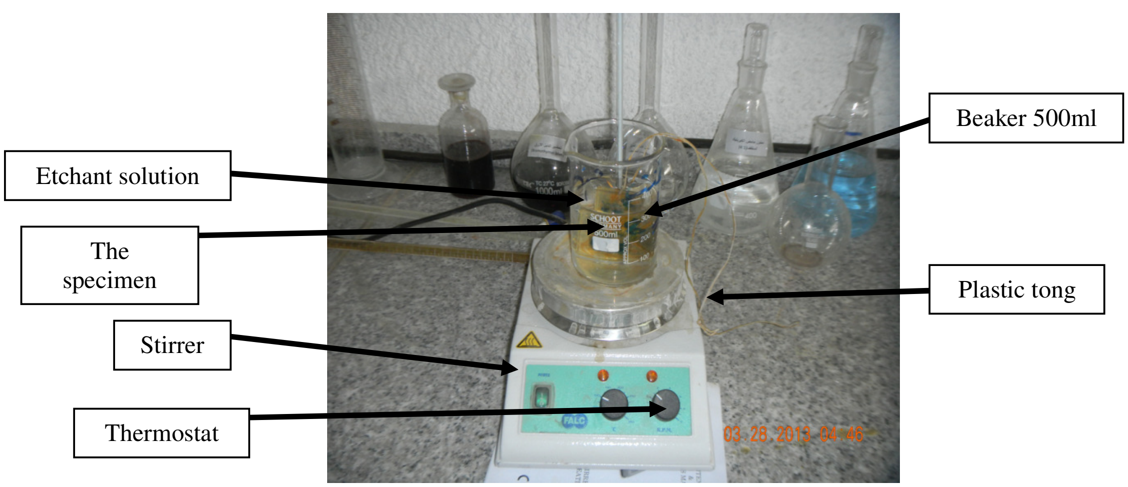


Figure (2): Chemical machining system

Wenking M – Lab (Bank Electronik – Intelligent controls GmbH GlessenerStrasse 60) was used in these tests to measure corrosion current, corrosion potential for samples of (20×20mm) dimensions. Scanning Probe Microscope AA3000 was used for microstructure test and also to measure the arithmetic mean value of the surface roughness, Ra. Three readings of Ra were recorded for each machining experiment.

4. CHEMICAL MACHINING PROGRAM

The alloy samples (with and without cold working) were chemically machined according to a program with different machining conditions. Design of experiments via Taguchi method and L'16 (3×4) mixed orthogonal array is utilized for the parametric design. Table 1 demonstrates the studied parameters with their levels for conducting the machining experiments.

Table (1): The studied parameters, their values, and their levels.

Parameter	Symbol	Unit	Level 1	Level 2	Level 3	Level 4
Cold Working	C_w	%	0	20	40	60
Machining Time	M_t	min	2	4	6	8
Machining Temperature	T	^{0}C	45	50	55	58

The "signal" to "noise" ratio, S/N, in decibels is used to determine an optimal combination of the studied parameters for a high surface finish. A category of "smaller is better" is used as the S/N ratio characteristic. This is expressed in [9] as:

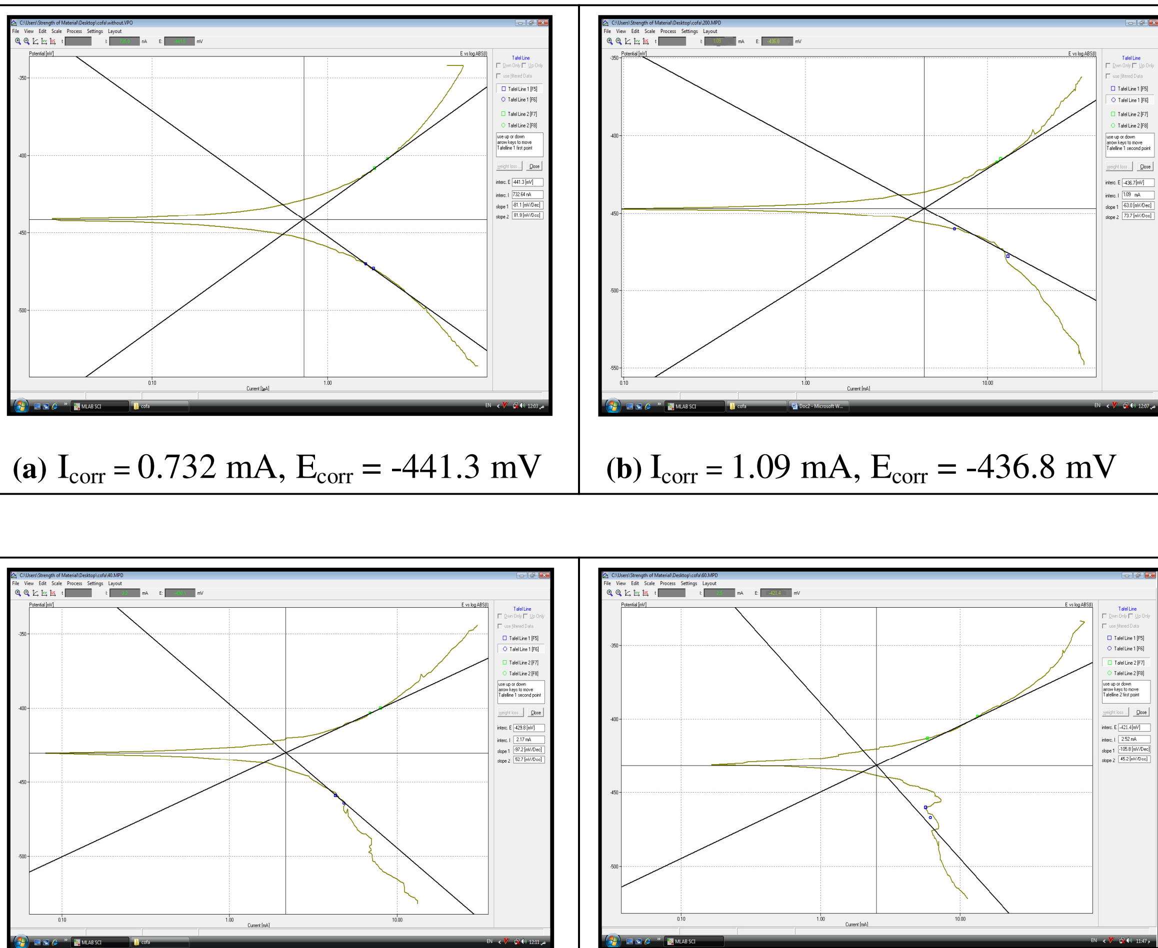
$$\frac{S}{N} = -10log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}(y_i^2)\right]\ ;\quad i = 1, 2, \ldots\ldots, n \qquad (1)$$

where *n* the number of observations, and y the observed data of the characteristic. This equation is used to determine the S/N ratio for the surface roughness.

5. RESULTS AND DISCUSSION

5.1. Results of the Tafel tests

All tests were carried out with identical conditions of 40 ºC. Fig.3 represents the Tafel curves obtained due to this test. The results indicate that an increase in percentage of cold working leads to increase in current of corrosion (I_{corr}) which increases etch rate. Increasing the percentage of cold working shifts the corrosion potential (E_{corr}) toward noble direction (less negative) because of cold working may form passive film which has more noble potential before its destroy.



(a) I_{corr} = 0.732 mA, E_{corr} = -441.3 mV

(b) I_{corr} = 1.09 mA, E_{corr} = -436.8 mV

(c) I_{corr} = 2.17 mA, E_{corr} = -429.8 mV

(d) I_{corr} = 2.52 mA, E_{corr} = -421.4 mV

Figure (3): Tafel curves for the alloy samples: (a) without cold working; (b) with 20% cold working; (c) with 40% cold working; (d) with 60% cold working

5.2. Results of the machining experiments

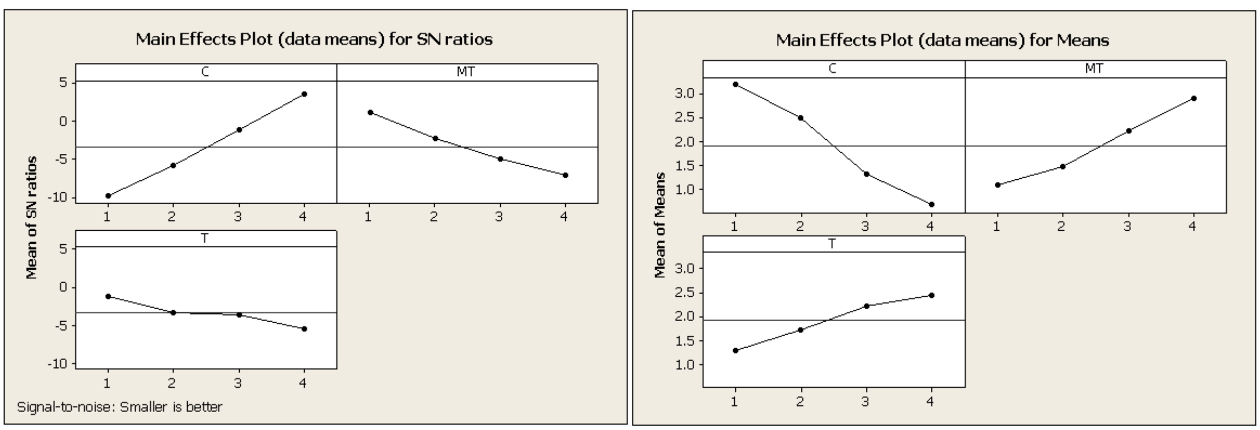
Table 2 demonstrates the results of the machining experiments conducted according to Taguchi L'16 (3×4) mixed orthogonal array. Three readings for the response characteristic, Ra, had been recorded with their average value. The values of the S/N ratio (in decibels) are shown also in the table.

5.3. Parametric Optimization for The Surface Roughness

Taguchi design analyses and its details are shown in Fig.4 and Table 3. It is clearly seen that the optimum combination of the studied affecting parameters according to the regarded category for minimum Ra is C_4 M_{t1}, and T_1, i.e., at 60% previous cold working, 2min machining time at 45^{0}C. Table 4 shows the ANOVA (with 95% confidence level) and F-test values with the P- value which reflects effectiveness of the individual studied parameters on the surface roughness. Table 4 indicates that the percentage of previous cold working is the most significant parameter for minimum surface roughness.

Table (2): Results of the machining experiments conducted according to Taguchi L'16 (3×4) mixed orthogonal array

No.	C_w (%)	M_t (min)	T (^{0}C)	Ra1 (µm)	Ra2 (µm)	Ra3 (µm)	Mean Ra (µm)	S/N Ratio (decibels)	Predicted value of Ra (µm)
1	1	1	1	2.40	2.50	2.30	2.40	-7.6092	2.353
2	1	2	2	2.80	2.95	2.65	2.80	-8.9515	2.634
3	1	3	3	3.32	3.42	3.22	3.32	-10.4254	3.473
4	1	4	4	4.24	4.42	4.02	4.24	-12.5265	4.489
5	2	1	2	0.84	0.87	0.81	0.84	1.5107	0.876
6	2	2	1	1.12	1.02	1.22	1.12	-1.0074	1.387
7	2	3	4	3.89	3.40	3.78	3.89	-11.3546	3.268
8	2	4	3	4.35	4.30	4.40	4.35	-12.7702	4.096
9	3	1	3	0.49	0.60	0.38	0.49	6.0526	0.4663
10	3	2	4	1.27	1.20	1.34	1.27	-2.0849	1.891
11	3	3	1	1.08	1.10	1.06	1.08	-0.6695	0.812
12	3	4	2	2.44	2.40	2.48	2.44	-7.7486	2.681
13	4	1	4	0.61	0.60	0.62	0.61	4.2926	0.360
14	4	2	3	0.71	0.80	0.64	0.71	2.8575	0.834
15	4	3	2	0.78	0.80	0.76	0.78	2.1562	0.668
16	4	4	1	0.58	0.60	0.56	0.58	4.7280	0.626



(a) (b)

Fig.(4): Results of Taguchi design analysis: (a) main effect plot for S/N ratios; (b) main effect plots of the studied factors

Table (3): The responses of S/N ratios and the means

Level	S/N ratios response			Means response		
	C_w	M_t	T	C	M_t	T
1	-9.878	1.062	-1.140	3.1867	1.0850	1.2950
2	-5.905	-2.297	-3.258	2.5000	1.4767	1.7150
3	-1.113	-5.073	-3.571	1.3200	2.2175	2.2192
4	3.509	-7.079	-5.418	0.6717	2.8992	2.4492
Delta	13.387	8.141	4.279	2.5150	1.8142	1.1542
Rank	1	2	3	1	2	3

Table (4): Analysis of Variance based on S/N ratio for the surface roughness

Source of variation	DF	SS	MS	F test	P
C	3	404.8	134.9	6.00	0.010
M_t	3	149.8	49.9	1.14	0.372
T	3	36.9	12.3	0.23	0.873
Error	12				
Total	15	674.8			

*DF – Degree of freedom; SS - Sum of Squares; MS - Mean Square

6. DEVELOPMENT OF MATHEMATICAL PREDICTIVE MODEL

Mathematical predictive model for the chemical machining process performance characteristic (i.e. surface roughness) had been developed in forms shown in table (5). Such models were constructed basing on the statistical data of the carried out machining experiments. Data fit ver.9 software was used for constructing these models basing on multiple regression analyses. The coefficient of multiple determination value for the non-linear quadratic polynomial is highest rank among all forms of other models. Hence, this model is selected to predict value of surface roughness with minimum error. So the final mathematical predictive model developed will be:

$$Ra = 110.4 + 1.73C_w + 9.98M_t - 5.17T + 0.0027C_w^2 + 0.29M_t^2 + 0.061T^2 - 0.432C_w \cdot M_t - 0.038C_w \cdot T - 0.242M_t \cdot T + 0.0084C_w \cdot M_t \cdot T \quad (2)$$

Table (5): Predictive models for the surface roughness

No.	Form of the Model	Model Definition	R^2
1	Three Parameter Polynomial	$Ra = a \cdot C_w + b \cdot M_t + c \cdot T$	0.85
2	Four Parameter Polynomial	$Ra = a \cdot C_w + b \cdot M_t + c \cdot T + d$	0.89
3	Four Parameter Exp. Polynomial	$Ra = \exp\,(a \cdot C_w + b \cdot M_t + c \cdot T + d)$	0.81
4	Power Function	$Ra = a \cdot C_w^b \cdot M_t^c \cdot T^d$	0.63
5	Non-linear Quadratic Polynomial	$Ra = a + b \cdot C_w + c \cdot M_t + d \cdot T + e \cdot C_w^2 + f \cdot M_t^2 + g \cdot T^2 + h \cdot C_w \cdot M_t + i \cdot C_w \cdot T + j \cdot M_t \cdot T + k \cdot C_w \cdot M_t \cdot T$	0.96

*R^2 – Coefficient of multiple determination; a, b, c, d, e, f, g, h, i, j, and k are constants.

The predicted values of Ra according to the developed model are demonstrated in Table 2. Table 6 shows the variance analyses for these predicted values, while Fig.5 shows their matching with the experimental values of surface roughness.

Table (6): Variance analyses for the predictive surface roughness

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob(F)
Regression	10	28.406	2.840	11.371	0.0075
Error	5	1.249	0.249		
Total	15	29.655			

*DF – Degree of freedom

To validate the developed predictive mathematical model two experiments with randomly selected conditions were conducted. The test results are demonstrated in Table 7, while Fig.6 shows surface roughness for the tested sample via Scanning Probe Microscope with an image size of 1994×1978 nm. It can be clearly noticed that the predicted by the model and the experimental results for the surface roughness bear good agreement with an error no more than 12%.

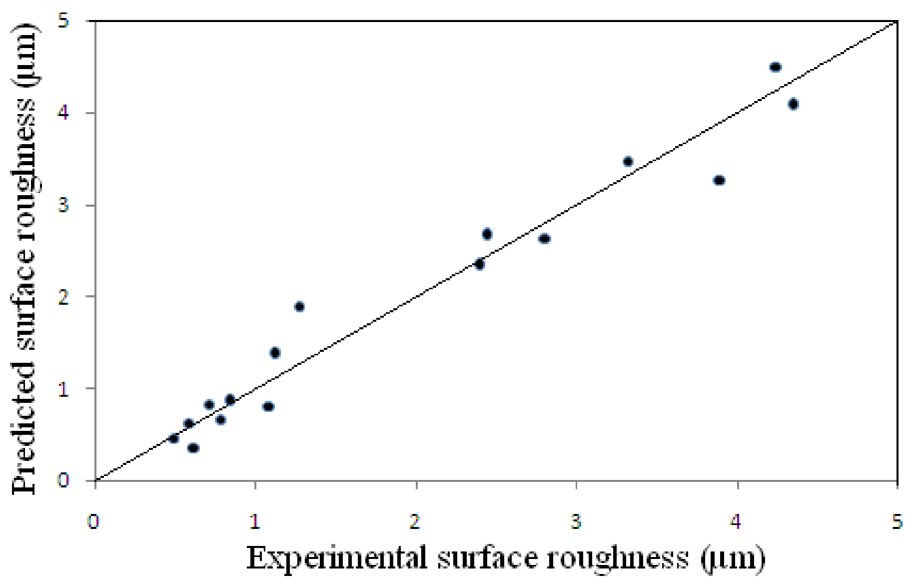
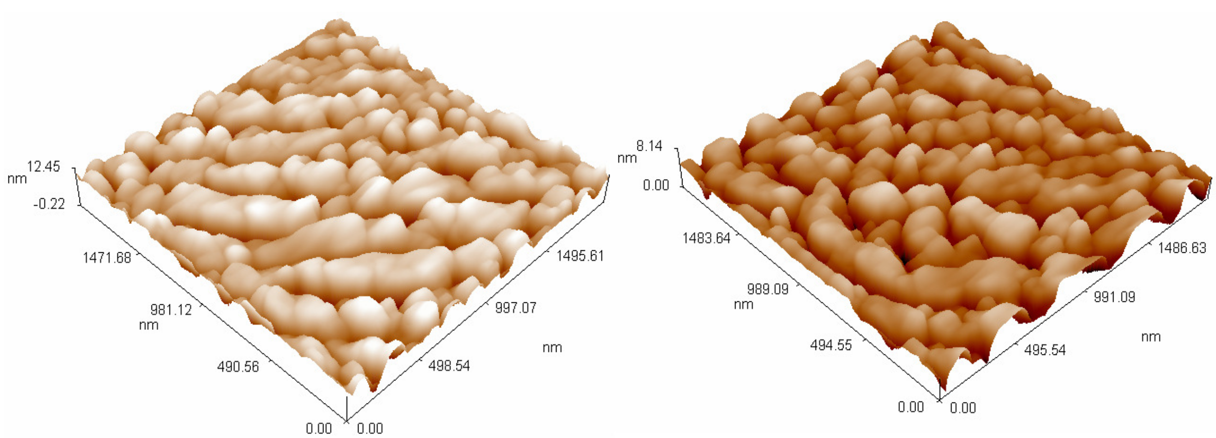


Fig.(5): Scatter plot of the experimental and predicted values of surface roughness.



(a) (b)

Figure (6): Surface roughness of chemically machined sample with: (a) C_w =20, M_t = 6min, T = 40^0C; and (b) C_w =60, M_t = 4min, T = 47^0C

Table (7): Confirmation test results for surface roughness

C_w (%)	M_t (min)	T (^{0}C)	Exp. Ra(μm)	Pred. Ra(μm)	Error (%)
20	6	40	1.68	1.746	4
60	4	47	1.12	0.98	12

7. CONCLUSIONS

Based on the detailed results the following conclusions can be stated:

1. Machining time, machining temperature and previous cold working are important variables that affect on finishing performance of chemically machined stainless steel 420. Among these variables cold working has the largest effect.
2. An optimum machining combination of stainless steel 420 for minimum surface roughness is C_4 M_{t1}, and T_1, i.e., at 60% previous cold working, 2min machining time at 45^{0}C.
3. An assessment of CHM can be achieved by empirical models for selecting the appropriate machining conditions for the required surface roughness.
4. The designed predictive model was successfully validated for selection of CHM parameters of stainless steel 420 using a mixture of acids (H_2O + HCl + HNO_3 + HF + HCOOH) as an etchant.

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