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Variables Affecting the Chemical Machining of Stainless Steel 420

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Abstract*— Chemical machining has a considerable value in the solution of machining problems that are constantly arising due to introduction of new materials and requirement for high surface finish and dimensional accuracy, complicated shape and special size which cannot be achieved by the conventional machining processes. The present work is aimed at studying the effect of machining temperature, machining time, and previous cold working on the metal removal rate and the surface finish of chemically machined samples of stainless steel 420 using a mixture of acids (H_2O + HCl + HNO_3 + HF + HCOOH) as an etchant. Alloy samples of (44.5×44.5×3mm) dimensions and cold rolled alloy samples with the same dimensions were chemically machined. Four machining temperatures (45, 50, 55, and 58°C) for each of which five machining times (2, 4, 6, 8, and 10min) were used as machining conditions. The results show that machining time, machining temperature and previous cold working have significant effect on chemical machining products, among these variables machining temperature has the largest effect. Surface roughness increases with the machining temperature and machining time, while it decreases with the previous cold working. Metal removal rate increases with machining temperature and decreases with previous cold working. Stainless steel 420 rolled samples can be chemically machined in [H2O + HCl + HNO3 + HF + HCOOH] etchants in optimum conditions at 40ºC for 6 min, while at 40 ºC for 6 min for the samples without cold working. An assessment of CHM was achieved by empirical modelsfor selecting the appropriate machining conditions for the required surface roughness and metal removal rate. The models were designed basing on multiple regression method via Mtb14 software.

***Keywords*-CHM, stainless steel, cold rolling, roughness, metal removal, regression.**

I. INTRODUCTION

The advancement of technology causes to the development of many hard-to-machine materials due to their high hardness, strength, brittleness, toughness and low machining 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 (Benedict.G.F, 1987). Moreover, the rise in temperature and the residual stresses generated in the work piece due to traditional machining processes may not be acceptable. These requirements have led to the development of non- traditional machining (NTM) 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 (Langworthy M., 1994). It has a considerable value in the solution of problems that are constantly arising as the result of the introduction of new materials.

All the common metals including aluminum, copper, zinc, steel, lead, and nickel can be chemically machined. Many exotic metals such as titanium, molybdenum, and zirconium, as well as nonmetallic materials including glass, ceramics, and some plastics, can also be used with the process (Blak.JT, DeGarmo, 2007). Chemical machining is an effective method for the machining of shallow holes and depressions, for profiling of the edges of sheet-metal, and for machining of shallow cavities of large surface areas particularly in light alloys (Drozda.T.J, 1989). CHM applications range from large aluminum alloy airplane wing parts to minute integrated circuit chips.

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 surface finish. Limited efforts have been directed towards improving the efficiency of the process. FadaeiTehrani A. in 2004 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 2004 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 2008 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 2009 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 2010 found that Cold rolled samples shows 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 present work is aimed at studying the effect of machining temperature, machining time, and previous cold working on the metal removal rate and the

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surface finish of chemically machined alloy samples of stainless steel 420. Each factor will take several levels in this study. The factor's levels represent the real work environment. Mathematical predictive models which can be used to optimize these variables will be designed.

II. MATERIALS USED IN THE PRESENT STUDY

A. *Alloy under study*

A sheet (1000×1000×3 mm) of stainless steel 420 with chemical composition shown in table (1) was used in this work. The analyses of the chemical composition was carried out in the State Company for Inspection and Engineering Rehabilitation, S.I.E.R/Baghdad-Iraq.

TABLE (1) CHEMICAL COMPOSITION OF THE ALLOY UNDER STUDY

Stainless Steel Alloy	C%	Si %	Mn %	Cr%	Mo %	Ni %	V%	Fe %
	0.09	0.3	9.7	15.66	0.002	0.6	0.08	Bal

To study the effect of previous cold working, 20% cold rolled samples had been prepared. All samples were cut to dimensions of (44.5×44.5mm).

B. *Maskant material*

Depending on the used alloy, methylethylketone peroxide was selected to prepare the maskant (El-Hofy.H.A.-G, 2005).

C. *Etchant solution*

The used etchant was a mixture of acids with concentrations demonstrated in table (2), as such chemical composition and concentration are effective to chemically machine the stainless steel used as a work piece (FadaeiTehrani.A, 2004).

TABLE (2) CHEMICAL COMPOSITION AND CONCENTRATION OF THE USED ETCHANT SOLUTION

Chemical composition	Etchant concentration (ml)
$H_2O + HCl + HNO_3 + HF + HCOOH$	1500 + 106 + 83 + 9 + 82

III. SAMPLES PREPARATION

A. *Samples Preparation for CHM*

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 °C 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. Figure (1) shows samples before and after the coating.

a. Sample before coating b. Sample after coating

FIG. (1) SAMPLES BEFORE AND AFTER COATING

The machining process was achieved via magnetic stirrer thermostat (made in England). It contains a thermostat to regulate the temperature of etchant during the machining operation and controller on velocity of stirrer as shown in Figure (2).

FIG. (2) CHEMICAL MACHINING SYSTEM

B. *Samples Preparation for tests*

Hardness test: Digital Display Micro Hardness Tester, Model HVS - 1000 (China made) was used. Suitable grinding papers (400, 800, 1000 and 2000) grit and polishing with alumina were used to prepare the surface of the samples. A load of 200 g with 10 seconds period for testing was regarded. The average of three readings was recorded.

Tafel test: Wenking M – Lab (Bank Electronik – Intelligent controls GmbH GlessenerStrasse 60) was used in this test to measure corrosion current, corrosion potential for samples of (20×20mm) dimensions.

Microstructure test: Microstructure tests of the samples were carried out by using Scanning Probe Microscope AA3000 Scanning Probe Microscope (Angstrom Advanced Inc, USA) that used for surface topography, microstructure and measure surface roughness testing.

IV. CHEMICAL MACHINING PROGRAM

The alloy samples (with and without cold working) were chemically machined according to a program included different machining conditions. Four machining temperatures (45, 50, 55, and 58°C) for each of which five machining times (2, 4, 6, 8, and 10min.) were used as the machining conditions. After each machining process, the surface roughness, weight loss and the metal removal rate, were recorded. The metal removal rate (MRR) was calculated basing on the weight loss after each experiment. The weight was measured via Sensitive weighing balance:

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ACCULAB Balance (made in china) with accuracy ±0.0001.

V. RESULTS AND DISCUSSION

A. Results of the Hardness tests

The hardness tests were carried out for the base alloy sample and for the cold worked alloy samples before and after the machining process. The results are demonstrated in table (3).

TABLE (3) RESULTS OF THE VICKERS HARDNESS TESTS

Alloy sample	Vickers hardness before CHM($g/\mu m^2$)	Vickers hardness after CHM($g/\mu m^2$)
Without cold working	323.32	319.37
With 20% cold working	415.96	413.74

The results indicate that the hardness of all samples does not affected by the chemical machining process, as no change in crystalline structure, no stresses induced by the process, as neither mechanical deformation nor exposure to high temperatures is involved.

B. Results of the Tafel tests

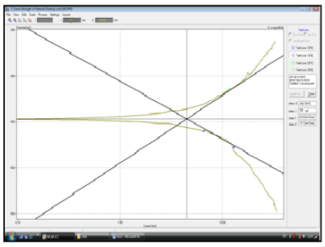
This test was used to determine the current and the potential needed to start corrosion. All tests were carried out with identical conditions of 40 ºC and 16 minutes duration. Figure (3) represent the Tafel curves obtained due to this test. The results of Tafel curves shown in table (4).

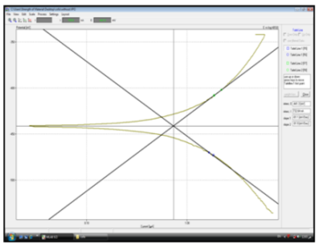
TABLE (4) RESULTS OF THE TAFEL TESTS

Alloy sample	$I_{corrosion}$(mA)	$E_{corrosion}$ (mv)
Without cold working	0.732	-441.3
With 20% cold working	1.09	-436.8

The results indicate the following:

- The required current to start the corrosion in CHM of alloy sample without cold working is less than that in the deformed alloy samples. Cold working leads to increase the value of the corrosion current density and deviation of corrosion potential in the negative direction which is more effective and least noble that is because of distortion in crystals lattice of cold worked samples by plastic deformation.
- Infer from corrosion current and potential of corrosion, the values of machining temperature must be little greater than the temperature at which Tafel test was carried out.





(a) With 20% cold working (b) without cold working
Fig. (3) tafel curve for the alloy sample

C. Effect of Machining Time on Ra and MRR

Figure (4) show the effect of the machining time on the surface roughness of the machined samples at different machining temperatures, while Figures (5) show how the machining time affects the metal removal rate for the same samples. The figures indicate the following:

- Increasing machining time leads to increase in surface roughness (Ra). This can be explained on the basis of the variety of the elements in the composition of the alloy. Increasing the machining time leads to increase dissolving the alloy to ions, active metal (the anode) corrodes at an accelerated rate and the more noble metal (the cathode) corrodes at a retarded rate and both share in the chemical reaction with the components of the etchant as shown in the following reactions:

$Fe \rightarrow Fe^{+2} + 2e^-$ ....(1)

$HCl \rightarrow H^+ + Cl^-$ ....(2)

$HNO_3 \rightarrow H^+ + NO_3^-$ ....(3)

$HF \rightarrow H^+ + F^-$ ....(4)

$2H^+ + 2e^- \rightarrow H_2$ ....(5)

During metallographic etching, twin and grain boundaries are preferentially attacked even the grain boundaries in very high purity. Metals are slightly grooved by appropriate etchants, the grain boundaries in impure metals and alloys are generally much more readily etched, primarily as a result of segregation to them the impurities and alloying additions. Grain-boundary regions may be preferentially attacked either because segregation makes them more active or because segregation makes them more noble; the grain boundary itself acts as a local cathode as stated in (Philip A. Schweitzer, 2010).

- Cold working leads to reduce surface roughness produced by machining for certain duration and at a certain temperature due to distortion of the grains and their orientation towards the rolling in sample structure.
- Decrease in metal removal rate can be noticed up to a machining time of 6 minutes and then suddenly rises and fall again due to increased dissolved metallic ions and its concentrations in the etchant.
- Metal removal rates for samples without cold working are lower than that for deformed samples for a certain machining time and machining temperature (2and 4min. at 45 and 50 ℃), therefore increasing degree of cold working leads to increase metal removal rate due to increase in the amount of deformation, higher formation of dislocation and their interaction with each other, which worsen corrosion resistance.
- Increase in machining temperature leads to increase in surface roughness. Machining temperature increases corrosion rate as a result of high power oxidization and mobility of ions. Also it has an effect on the etchant's ability to hold the dissolved metal content in solution.

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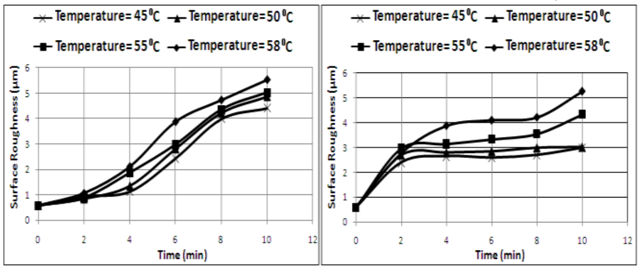
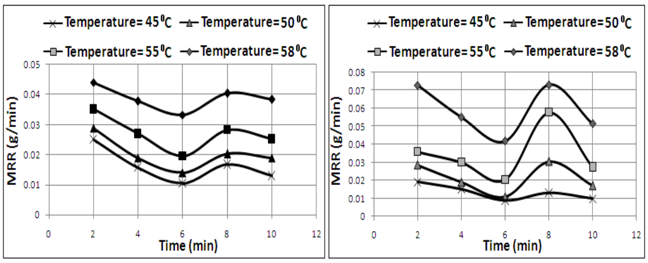


(a) 20% cold worked sample (b) base alloy sample

FIG. (4) EFFECT OF MACHINING TIME ON SURFACE ROUGHNESS FOR THE ALLOY SAMPLES MACHINED AT DIFFERENT MACHINING TEMPERATURES



(a)20% cold worked sample(b) base alloy sample

FIG. (5) EFFECT OF MACHINING TIME ON METAL REMOVAL RATE FOR THE ALLOY SAMPLES MACHINED AT DIFFERENT MACHINING TEMPERATURES

VI. OPTIMIZATION OF THE MACHINING CONDITIONS

The results of the machining experiments showed that machining temperature, machining time and cold working have significant and interaction effects on the roughness of the machined surface and on the metal removal rate. Optimum combination at these variables can be obtained by designing mathematical models representing their relations with the required output of the machining process – roughness and metal removal rate.

Such models were constructed basing on the statistical data of the carried out machining experiments. Mtb15 software was used for constructing these models basing on the analyses of regression.

Table (5) demonstrates the constructed mathematical models and the values of the statistical coefficients, while Fig. (6) shows the matching between the experimental values of surface roughness, Ra, and metal removal rate, MRR, and their predicted values due to the designed models. The constructed empirical models indicate the following:

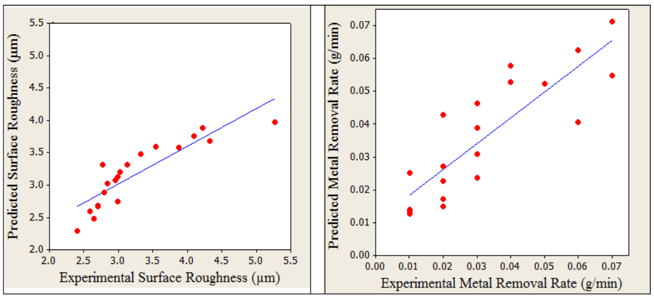
- Machining temperature has a greater effect on Ra and MRR in comparison with the machining time and this is independent of the cold working
- Machining for a larger duration increases the roughness of the produced surfaces and reduces the metal removal rate, and this is not affected by amount of cold working.
- Previous cold working reduces Ra and also MRR but at a certain temperature for a certain time.

TABLE (5) EMPIRICAL MODELS FOR RA AND MRR

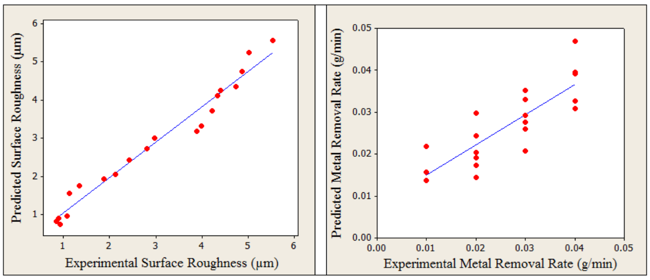
Percentage of C.W%	Empirical model	R^2 Square Root of SME	F Tests to Fit	S Standard deviations
0	$Ra = 0.0085 * t^{0.113} * T^{1.45}$	88	50.74	0.026
	$MRR = 10^{-11} * t^{-0.191} * T^{5.62}$	85	41.56	0.116
20	$Ra = 0.0061 * t^{1.09} * T^{1.06}$	99.4	1001.8	0.023
	$MRR = 12.8 * 10^{-8} * t^{-0.261} * T^{3.2}$	72	19.65	0.105

* t- Machining Time in min. ; T- Machining Temperature in °C

Fig (6) shows that the predicated values of the surface roughness and the metal removal rate basing on the designed models are close match of their experimental values.

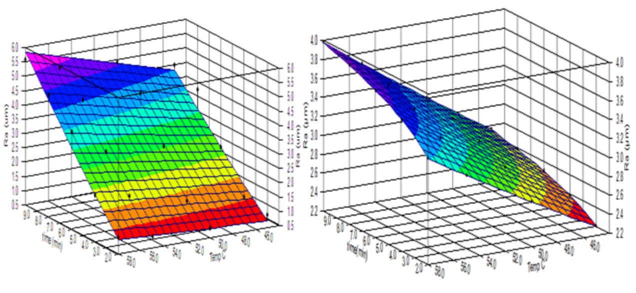


(a) For 0% cold working



(b) For 20% cold working

FIG (6) SCATTER PLOT OF THE EXPERIMENTAL AND EMPIRICAL VALUES OF RA AND MRR



(a) (b)

FIG. (7) RELATION BETWEEN SURFACE ROUGHNESS (RA), MACHINING TIME AND MACHINING TEMPERATURE FOR SAMPLES: (A) WITH 20% COLD WORKING, AND (B) WITHOUT COLD WORKING.

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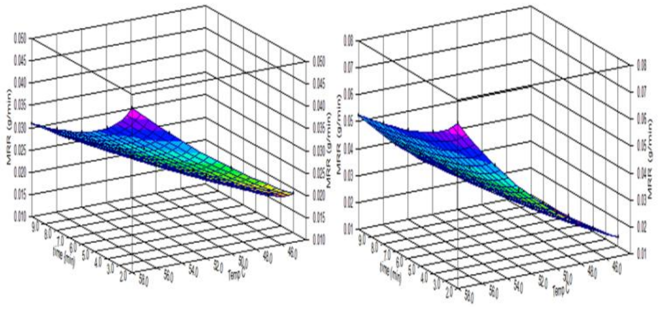
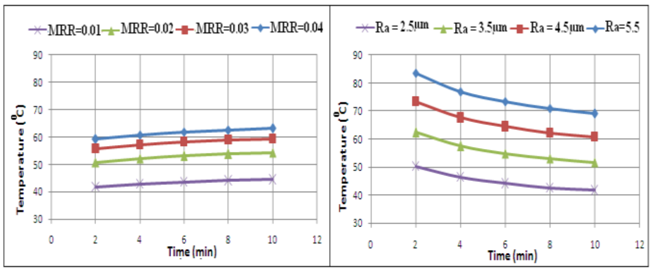


(a) (b)

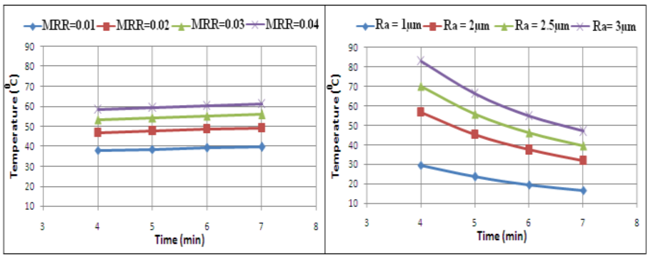
FIG.(8) RELATION BETWEEN METAL REMOVAL RATE, MACHINING TIME AND MACHINING TEMPERATURE FOR SAMPLES: (A) WITH 20% COLD WORKING, AND (B) WITHOUT COLD WORKING.

Figure (9) and Fig. (10) were constructed basing on the designed mathematical models .The figures represent the values of the surface roughness and the metal removal rate in the machining temperature – machining time plane.



(a) (b)

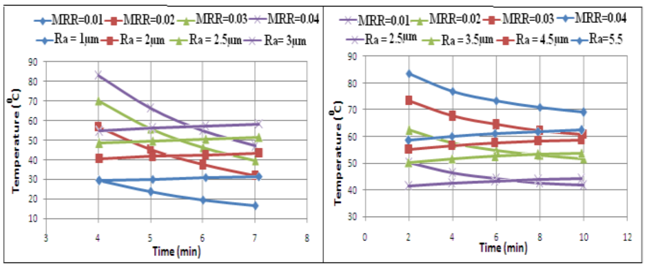
FIG.(9) MACHINING TEMPERATURE – MACHINING TIME PLANE FOR SAMPLES WITHOUT COLD WORKING: (A)SURFACE ROUGHNESS (B) METAL REMOVAL RATE



(a) (b)

FIG.(10) MACHINING TEMPERATURE – MACHINING TIME PLANE FOR SAMPLES WITH 20% COLD WORKING: (A)SURFACE ROUGHNESS (B) METAL REMOVAL RATE

Figure (11) were constructed by superimposing the values of the surface roughness and the metal removal rate contours in the machining temperature – machining time plane.



(a) For cold worked sample (b)For sample without cold working

FIG. (11) SURFACE ROUGHNESS AND METAL REMOVAL RATE IN A TEMPERATURE – TIME PLANE

Figure (11) give an ability to select an optimum combination of machining temperature and machining time to obtain required values for surface roughness and metal removal rate. Finally, the results of optimum conditions for each degree of cold working are shown in table (6).

VII. RESULTS OF TESTS BY SCANNING PROBE MICROSCOPE

Scanning Probe Microscope was used to test samples before and after the chemical machining. Machining conditions were used according to the methodology discussed and basing on Figure (11). These conditions are demonstrated in table (6) .

TABLE (6) CHEMICAL MACHINING CONDITIONS FOR SAMPLES TESTED BY SPM

Degree of cold working	Temperature ºC	time (min)
0% cold working	45	6
20% cold working	43	6

Figures (12) and Fig.(13) show microstructure, topography and surface roughness for the tested sample by using Scanning Probe Microscope with/without cold working before and after chemical machining. The image size is 1994×1978 nm.

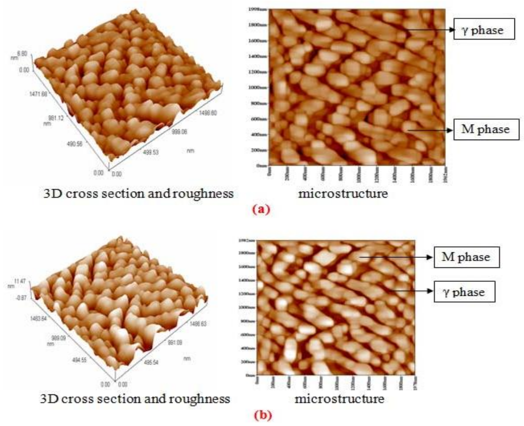


FIG. (12) SURFACE ROUGHNESS AND MICROSTRUCTURE FOR THE SAMPLE WITHOUT COLD WORKING (A) BEFORE CHM (B) AFTER CHM

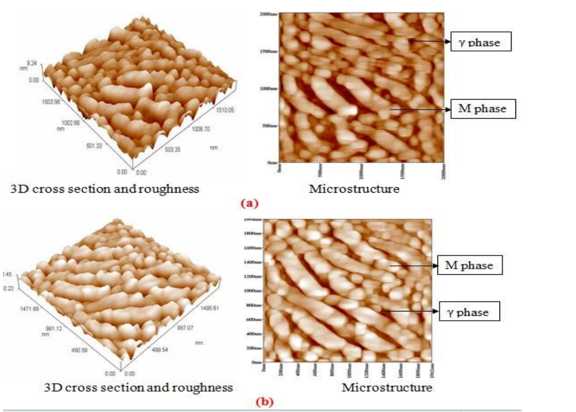


FIG. (13) SURFACE ROUGHNESS AND MICROSTRUCTURE FOR THE SAMPLE WITH 20% COLD WORKING (A) BEFORE CHM (B) AFTER CHM

The figures indicate the following:

- All grains of the deformed samples were elongated in the direction of cold rolling. This elongation is not affected by the chemical machining process.
- Average of measured surface roughness of the machined samples without cold working is 2 µm, which is too close to that can be calculated by the designed empirical model where Ra =2.5µm and MRR=0.01 g/min. The average surface roughness for machined samples with 20% cold working was 1.68µm, which is also close to that can be calculated by the designed empirical model, where Ra = 2µm and MRR=0.01 g/min. This indicates the confidence of the designed empirical models.
- There are no metallurgical defects on the machined surfaces due to chemical machining process.
- Microstructure is consisting of two phases (γ + M), dark and light color, austenite phase (γ) and martensite phase (M). After chemical machining, there is no change in microstructure, but an increase in martesite phase (M) had been occurred. For samples with 20% cold working the microstructure before chemical machining contains elongated martensite (M) within matrix of austenite phase (γ) in crystal lattice, as the transformation of the induced plasticity causes the grain size to be decreased.

VIII. 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 chemical machining products; among these variables machining temperature has the largest effect.
2. Surface roughness of chemically machined parts increases with the machining temperature and machining time.
3. Surface roughness of chemically machined parts decreases with the previous cold working of the work piece.
4. Metal removal rate increases with machining temperature and decreases with previous cold working.
5. Products of stainless steel 420 without cold working can be chemically machined in [H_2O + HCl + HNO_3 + HF + HCOOH] etchants in optimum conditions at temperature 45ºC and time 6 min.
6. Products of stainless steel 420 with 20% cold working can be chemically machined in [H_2O + HCl + HNO_3 + HF + HCOOH] etchants in optimum conditions at temperature 40 ºC and time 6 min.
7. An assessment of CHM can be achieved by empirical modelsfor selecting the appropriate machining conditions for the required surface roughness and metal removal rate.

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Babylon University, Iraq to develop mechanical and physical characteristics of advanced materials.

• The number of master's students who have been supervising them (14.

• The number of the many local conferences.

• The number of international conferences in which the participant research (14).

• Chairman of the international auditors. Arica British institution

• Dr. Kadhim F. Abdulhussein Al-sultani.

• Degree: Associate Professor.

• Marital Status – Married

• The number of children – 7.

• Bachelor of Chemical Engineering - University of Technology - Baghdad. Materials Engineering 1990.

• Master of Chemical Engineering - University of Technology - Baghdad. Industrial units 1999.

• PhD in Chemical Engineering - University of Technology - Baghdad. Corrosion Engineering 2003.

• Dean of Materials Engineering College.

• Number of research published and accepted for publication more than 30 papers. Including 8 research published in international journals.

• The No. Patented – (1).