Interaction Effect of Feed Rate and Cutting Speed in CNC-Turning on Chip Micro-Hardness of 304- Austenitic Stainless Steel

G. H. Senussi

Abstract—The present work is concerned with the effect of turning process parameters (cutting speed, feed rate, and depth of cut) and distance from the center of work piece as input variables on the chip micro-hardness as response or output. Three experiments were conducted; they were used to investigate the chip micro-hardness behavior at diameter of work piece for 30[mm], 40[mm], and 50[mm]. Response surface methodology (R.S.M) is used to determine and present the cause and effect of the relationship between true mean response and input control variables influencing the response as a two or three dimensional hyper surface. R.S.M has been used for designing a three factor with five level central composite rotatable factors design in order to construct statistical models capable of accurate prediction of responses.

The results obtained showed that the application of R.S.M can predict the effect of machining parameters on chip micro-hardness. The five level factorial designs can be employed easily for developing statistical models to predict chip micro-hardness by controllable machining parameters.

Results obtained showed that the combined effect of cutting speed at it's lower level, feed rate and depth of cut at their higher values, and larger work piece diameter can result increasing chi micro-hardness.

Keywords—Machining Parameters, Chip Micro-Hardness, CNC Machining, 304-Austenic Stainless Steel.

I. INTRODUCTION

MICRO-HARDNESS of the chip plays a very important role in change of properties of a machined part and tool life[1]. It has an influence on the surface roughness of the work piece which has an influence on mechanical properties such as wear resistance, fatigue strength, and corrosion resistance [2].

The shear strain acceleration governs the machining parameters like tool chip interface temperature, shear angle, etc. It is therefore speculated that micro-hardness of the chip for the same machining condition but for different shear strain accelerations would be different. The micro-hardness of chip obtained during accelerated cutting is governed by shear strain acceleration and it is governing parameters and from results

Author is with Faculty of Engineering, Omar Al-Mokhtar University, Baitha, Libya.

obtained, the micro-hardness of chips during accelerated cutting is governed by shear strain rates as well as shear strain acceleration and its governing parameters like, spindle speed, feed rate, and taper angle. Micro-hardness values for facing are generally the highest. For taper turning, micro-hardness values lay between those of facing and longitudinal turning, change in micro hardness is more drastic in facing [3].

The micro-hardness variation within and around the cutting zone by freezing the chips using a quick stop device and their primary concern was to determine the thickness of the primary shear deformation zone. By locating a boundary where a sadden change in the micro-hardness in the gird pattern marked on the work piece, took place. Since no much literature is a valuable to show the independent machining parameters affect on the micro-hardness of the chips obtained during machining [4].

The present work concerns with the optimization of the machining parameters in CNC-Turning machine, and study their effects on the chip micro-hardness of stainless steel work piece. Predicting of some statistical model to select the optimum combination effect of machining variables such as cutting speed, feed rate, depth of cut, and distance from the cent for work piece as the input, and the chip micro-hardness as response. Models will be designed using the methods of experimental design technique combined with regression analysis and analysis of variance then supported by using the response surface methodology. Analysis and checking of the developed models should be done by testing the significance of the regression coefficients. The effect of machining parameters and their significant interaction on surface roughness will be studied based on the data obtained by the developed models.

The interaction effects of machining parameters on the response will be presented graphically. Response surface methodology applying three factors with five levels of center composite rotatable factorial design was used for planning, execution and development of mathematical models. These models will be useful not only for predicting the chip micro-hardness but also for selecting the process parameters for achieving a good response (chip micro-hardness).

II. APPLICATION OF R.S.M ON SURFACE ROUGHNESS

The main problem in getting a good chip micro-hardness by

turning process is in the selection of the optimum combination of input variables, which can be solved by the development of mathematical models. The goal of the resent work is to use RSM to develop statistical models capable of accurate prediction of chip micro-hardness. CNC-Turning machine was used to prevent any error in the input data (Independent variable) and output data (dependent data). The independent variables are, cutting speed (v), Feed rate (f), Depth of cut (d) and distance from the cent for work piece (D).The working rang of the process variables and their decided levels of the parameters and their notation are given in Table I.The upper limit of a factor was coded as +1.682 and lower limit as -1,682 for experimental chip micro-hardness [5, 6, and 7] .The coded values for intermediate value as 0. The five levels of the three variables coded values were calculated from the following relationship:

$$X_i = 2 *[2X-(X_{max} + X_{min})] / (X_{max} + X_{min}) \qquad (1)$$

Where Xi is the required coded value of a variable X, X is any value of variable from X_{min} to X_{max}, X_{min} is the lower level of variable; X_{max} is the upper level of variable.

TABLE I
WORKING RANGE AND THE LIMITS OF CONTROL PARAMETERS FOR CHIP-MICRO-HARDNESS

Processes control (Parameters	Working rang		Limits of chip-micro-hardness				
	Min.	Max	-1.682	-1	0	1	1.682
Cutting speed v[m/min]	160	200	160	170	180	190	200
Depth cut d[mm]	0.4	2.0	0.4	0.8	1.2	1.6	2.0
Feed rate f[mm/rev]	0.04	0.2	0.04	0.08	0.12	0.16	0.20

The selected experimental matrix is a 2^k full factorial central rotatable fixed levels design. The total number (N) of the experimental runs (treatment combinations) for these factors is given by [8, 9, and 10] as:

$$\alpha = (2)^{k/4} \quad k < 5 \qquad (2)$$

$$\alpha = (2)^{(k-1)/4} \quad k \geq 5 \qquad (3)$$

For the present investigation, where k=3, there will be 8 corner, 6 stars, and 6 center runs yielding total number of points, $N = 20$ with star arm, $\alpha = 1.682$. These runs and their combination sets are listed in what is called "Experimental design matrix". Table I gives this design matrix with central composite rotatable, fixed levels. The complete design matrix consists of 20 sets of coded treatment combinations. It comprises a full replication of $2^3 = 8$ factorial design plus 6 center and 6 start points respectively. All machining variables at the intermediate level (0) constitute the center points and combinations of each of machining variables at either its

lowest (-1.682) level or its highest level (+1.682) with the two variables at the intermediate levels constitute at the star points [10]. Thus 20 experimental runs were allowed in the estimation of the linear quadric, and two-way interactive effects the process parameters.

III. THE MATHEMATICAL MODEL TO DESCRIBE THE EXPERIMENT

The response function representing any of machining parameters (v, f, d) can be expressed as [9]:

$$Y = fun (X1, X2, X3) \qquad (4)$$

Where: Y is the response.

X's are the coded levels of the k quantitative factors.

The statistical models $F_1, F_2,$ and F_3 for each of responses will be designed as Y_1, Y_2 and Y_3 for chip micro-hardness at diameters (D_1, D_2, D_3) equal 30[mm], 40[mm], 50[mm] respectively. The relationship which was selected is a second degree response surface expressed as follows:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{11} X_1^2 + b_{22} X_2^2 +$$
$$b_{33} X_3^2 + b_{12} X_1 X_2 + b_{13} X_1 X_3 + b_{23} X_2 X_3 \qquad (5)$$

The 20 run experimental treatment combinations (run) were conducted as designed by the experimental matrix shown in Table II, also the results obtained are shown in Table II.

TABLE II
ESTIMATED VALUES OF REGRESSION COEFFICIENTS AT DIAMETER (D=30 MM)

No	Regression coefficient	Value	T(10)	P-level	Parameter
1	b_o	347.92	58.399	0.002	
2	b_1	36.58	9.255	0.007	v^*
3	b_2	48.31	12.221	0.01	f^*
4	b_3	-32.64	-8.258	0.04	d^*
5	b_{11}	-25.13	-6.532	0.0001	v^{2*}
6	b_{22}	28.68	7.456	0.005	f^{2*}
7	b_{33}	1.03	0.266	0.7954	d^2
8	b_{12}	16.31	3.159	0.0102	vf^*
9	b_{13}	-19.94	-3.860	0.0032	vd^*
10	b_{23}	12.69	2.457	0.0339	fd^*
Note: *significance					

TABLE III
EXPERIMENTAL DESIGN MATRIX AND OBSERVED VALUES OF CHIP MICRO-HARDNESS AT DIFFERENT DIAMETERS (D) = 30, 40 AND 50[MM]

Run No.	Experimental design			Chip Micro-hardness μH(VPN)		
	$X_1(v)$	$X_2(f)$	$X_3(d)$	D = 30 [mm]	D = 40 [mm]	D = 50 [mm]
1	-1	-1	-1	319	330	341
2	-1	-1	+1	246.5	255	263.5
3	-1	+1	-1	348	360	272
4	+1	-1	-1	391.5	405	418.5
5	-1	+1	+1	348	360	372
6	+1	-1	+1	261	270	279
7	+1	+1	-1	507.5	525	542.5
8	+1	+1	+1	406	420	434
9	-1.682	0	0	217.5	225	232.5
10	+1.682	0	0	333.5	345	356.5
11	0	-1.682	0	348	360	372
12	0	+1.682	0	507.5	525	542.5
13	0	0	-1.682	391.5	405	418.5
14	0	0	+1.682	304.5	315	325.5
15	15	0	0	333.5	345	356.5
16	16	0	0	348	360	372
17	17	0	0	377	390	403
18	18	0	0	348	360	372
19	19	0	0	348	360	372
20	20	0	0	333.5	345	356.5

The second order polynomial (regression) can be expressed by equation number 5 or:

$$Y = b_\circ + b_1 v + b_2 f + b_3 d + b_{11} v^2 + b_{22} f^2 + b_{33} d^2 + b_{12} v.f + b_{13} v.d + b_{23} f.d \qquad (6)$$

where Y is the response (Chip Micro-hardness).

Let F_1, F_2 and F_3 representing the response surface roughness at diameters (D) equal 30, 40, and 50[mm] respectively. Using computer software statistical program (S.P.S) to the estimated values of the regression coefficients for each model, the following results given in Table IV were obtained for the regression coefficients for model I (F_1) at diameter 30[mm].

T-test [11] was achieved to test the significance of the coefficient of the three models at significant level of (α = 0.05) for all the models. For example: the coefficient b_1 in the model F_1 is significant, because P-level of this coefficient less than 0.05(P-level of coefficient b_1 = 0.007 < α = 0.05). This mean, that the coefficient b_1 has effect on the response of model F_1, on the other hand, the (P-level) of coefficient b_{11} in model F_1 is more than 0.05 (P-level of coefficient b_{33} =

0.7954 > α = 0.05).This means, it has no effect on the response of model F_1 and so on for all other coefficients.

The adequacy of the model was tested by using ANOVA technique at confidence level of 95%. It was found that all models are adequate since (P -level) (0.00001) is less than the significant level (0.05) which means that the model has a significant meaning [5]. Table IV shows the ANOVA analysis for the model 1 and the other two models were done by same way.

TABLE IV
ANOVA ANALYSIS FOR THE MODEL

Effect	Sum of squares	D.F	Mean squares	F-level	P- level
Regression	94563.6	9	10507.06	49.24039	0.00001
Residual	2133.8	10	213.3831		
Total	96697.4				

After dropping out the non-significant terms from Table IV, the equations for the models can be written as follow:

Model F_1 (chip micro-hardness at diameter 30 mm)

$$347.92 + 36.58X_1 + 48.31X_2 - 32.64X_3 - 25.13 X_1^2 + 28.68 X_2^2 + 16.31X_1X_2 - 19.94X_1X_3 + 12.69X_2X_3 \qquad (9)$$

Model F_2 (chip micro-hardness at diameter 40 mm):

$$359.94 + 37.84X_1 + 49.97X_2 - 34.15X_3 - 25.88 X_1^2 + 29.79 X_2^2 + 16.87X_1X_2 - 20.63X_1X_3 + 13.13X_2X_3 \qquad (10)$$

Model F_3 (chip micro-hardness at diameter 50 mm):

$$371.90 + 39.10X_1 + 51.64X_2 - 35.28X_3 - 26.75 X_1^2 + 30.78 X_2^2 + 17.44X_1X_2 - 21.31X_1X_3 + 13.56X_2X_3 \qquad (11)$$

IV. RESULTS AND DISCUSSIONS

The validity of the obtained final models can be judged from their coefficients of correlation (r) which are found as 0.97, 0.98, and 0.97 for models F_1, F_2, and F_3 respectively. This validity can also be judged from Figs. 1, 2, and 3 respectively which show the relationship between the measured and computed values of chip micro-hardness. These graphs indicate that the above equations 9, 10 and 11 express very close relation between the measured (observed) and computed (calculated) values of chip micro-hardness and the relationship and correlation between the dependent variables (response or chip micro-hardness), And independent variables (machining Parameters *v, f* and *d*) are found 0.97, 0.98 and 0.98 for F_1, F_2, and F_3 respectively.
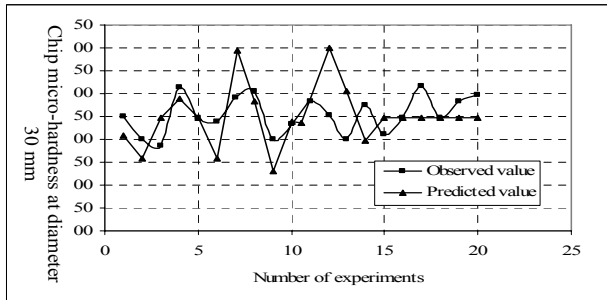
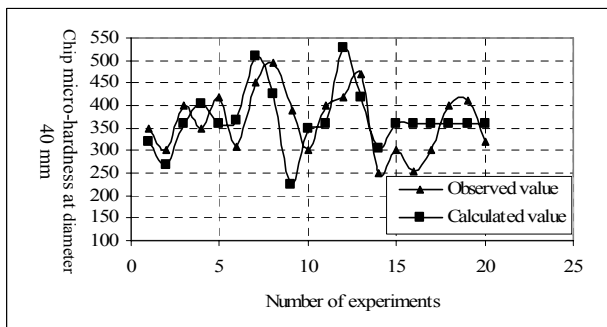Fig. 1 Observed and Estimated chip micro-hardness at D = 30 [mm] According to Model (F_1)

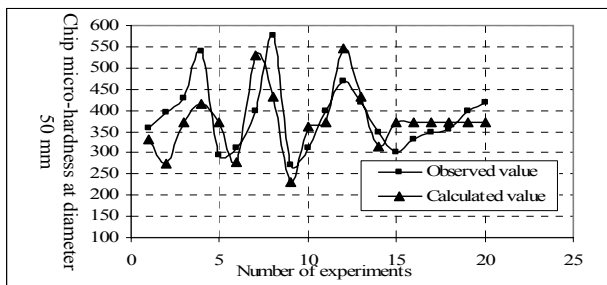Fig. 2 Observed and Estimated chip micro-hardness at D = 40 [mm] According to Model (F_2)

Fig. 3 Observed and Estimated chip micro-hardness at D = 50 [mm] According to Model (F_3)

From Fig. 4 it can be seen that as cutting speed is increased the chip micro-hardness is decreased. It is found that the lowest values of chip micro-hardness were at the highest values of cutting speed mean at level (200 m/min). This was because, as cutting speed is increased the cutting forces are decreased thus lowering the amount of heat generation and as a result the rate of strain hardening is decreased. Also at high cutting speed and the time allowed to machine the surface is shorter meaning that the time during which the tool is in contact with the work piece is short, so heat generation due to the mechanism of cutting and friction which is a function of rubbing between tool and work piece as of a small amount. A small quantity of heat which is transferred to the chip does not result microstructure change of the chip and strain hardening is of negligible effect compared with lower cutting speed.
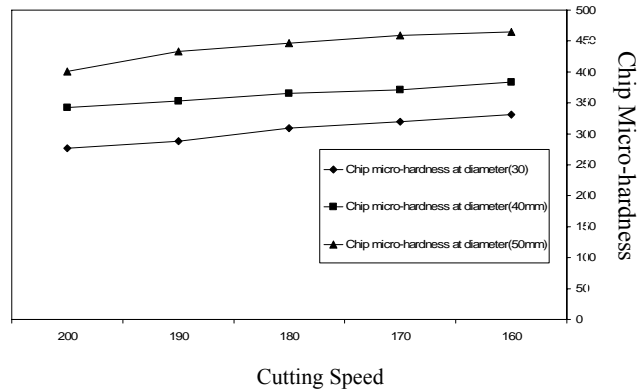

Fig. 4 Effect of cutting speed on chip micro-hardness at diameter 30, 40, and 50 mm.

Also from Fig. 4 it is clear that chip micro-hardness is increasing as the distance of machining surface from the work piece center is increased. The higher value of micro-hardness was achieved at a distance of 25 mm (50 mm diameter) from the center of the work piece. Continuing in machining showed lower micro-hardness of the chip due to that shearing forces are decreased as the diameter of work piece is decreased leading to a decrease in the heat generated and the plastic deformation of the chip. Since the work piece shaft is hot rolled, the surface layer has hardness higher than the core. This is due to the rolling technique and a high cooling rates at the surface, resulting is higher hardness.
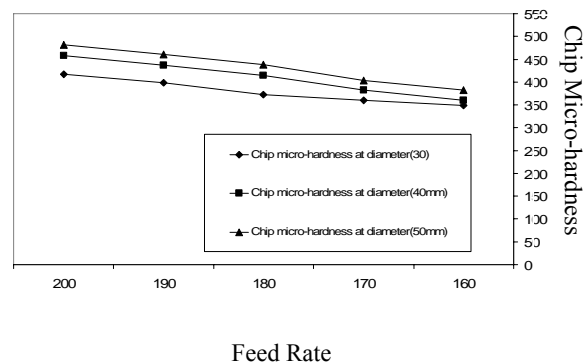

Feed Rate
Fig. 5 Effect of feeding rate on chip micro-hardness at diameter 30, 40, and 50 mm.

In Fig. 5, feeding rates is shown to have its effect on chip micro-hardness; however, as feed rate is increased the chip micro-hardness is increased relatively up to the highest feed rate at level (200 m/min). Thus as feed rate is increased, a large amount of metal removed is subjected to higher temperature and plastic deformation because of an increase in cutting force and normal force which result in temperature increase of the chip and plastic deformation which results hardening of the chip especially at the interface between the chip and tool. This interface is subjected to a burnishing mechanism which affects the hardness of the chip besides the effect of cutting shear force. The interaction effect of both source results is higher hardness.

The chip micro-hardness is increased as the distance of cutting surface from the center of work piece is increased. The same is observed, however, at a distance of 25 mm (50 mm diameter) from the center of the work piece the higher value of chip micro-hardness was observed, due to the above reasons mention with cutting speed effect on chip micro-hardness.
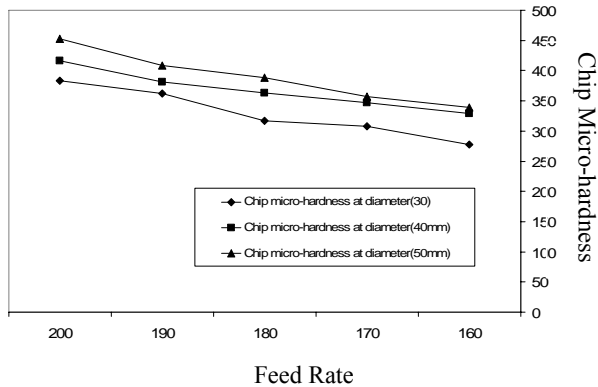

Fig. 6 Effect of depth of cut on chip micro-hardness at diameter 30, 40, and 50 mm.

Fig. 6 shows the effect of depth of cut on chip micro-hardness, where higher values of chip micro-hardness are obtained with increasing depth of cut. Up to the level (1.682), where a longer surface contact between the cutting tool edge and metal removed takes place and resulting in a directional flow of the chip over the tool face and higher cooling rate accompanied by an increase in chip micro-hardness from the surface of contact toward the outer surface of chip. A thickness of chip is removed by higher cutting force thus large amount of heat is generated and higher rates of cooling thus higher value of hardness is resulted.

The distance of cutting tool from the center of work piece has also its effect on the chip micro-hardness, and highest values are obtained at 25 mm (50 mm diameter) from the center due to the same source and reasons mentioned with cutting speed effect on chip micro-hardness.

Figs. 7, 8, and 9 shows that as the feed rate increases at low cutting speed the chip micro hardness increases and then starts to decrease with increased rates of cutting speed until it reaches its minimum value at feed rate level equal 1.682 and cutting speed at its maximum level value (1.682). For low cutting speed values, chip micro-hardness is increased with increase in feed rate while for high cutting speed values, it is decreased at low cutting speed. An increase in feed rate caused an increase in shear strain rate hence strain hardening resulted the increase in chip micro-hardness. At higher cutting speed, the effect of thermal softening dominates, leading to a decrease in micro-hardness.
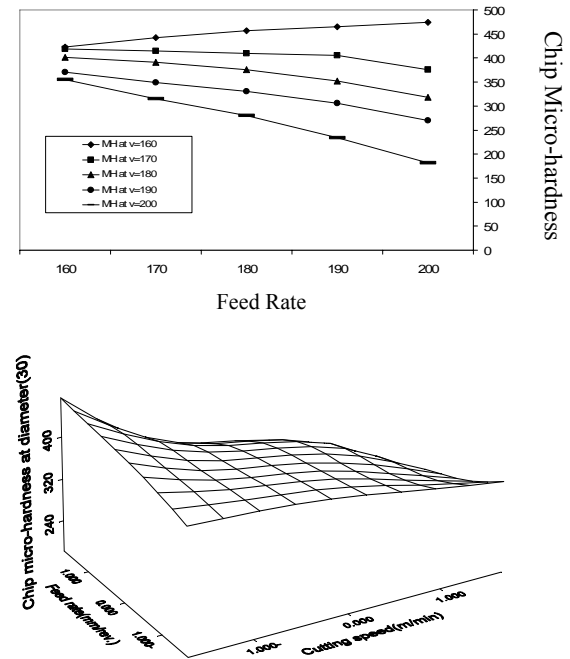

Fig. 7 Interaction effect of cutting speed and feed rate on chip micro-hardness at Diameter = 30 [mm].
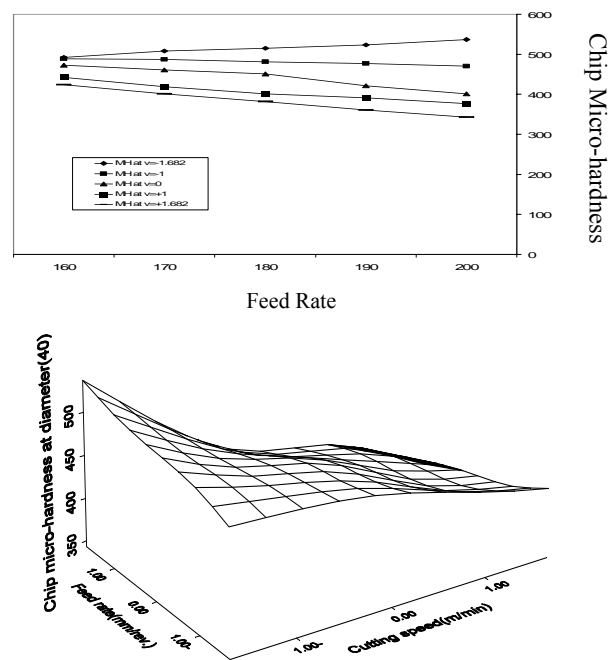

Fig. 8 Interaction effect of cutting speed and feed rate on chip micro-hardness at Diameter = 40 [mm].
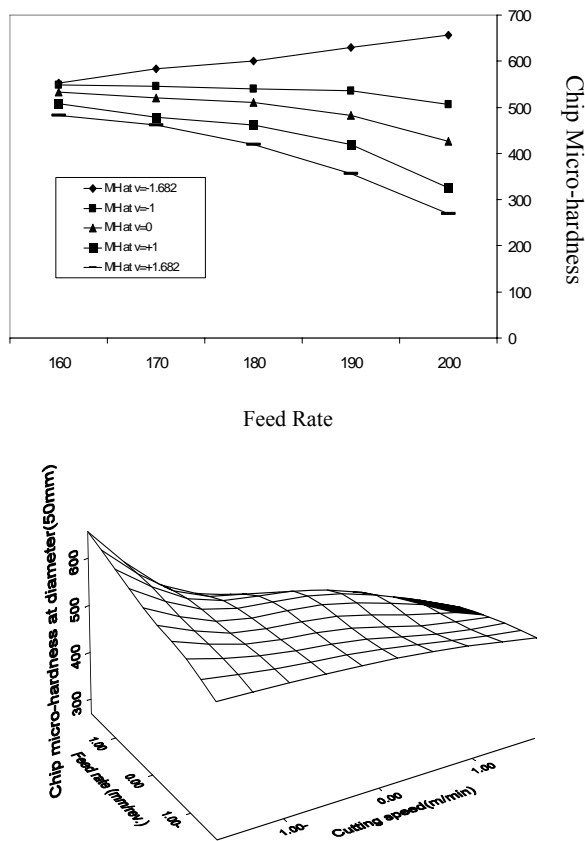
Feed Rate

Fig. 9 Interaction effect of cutting speed and feed rate on chip micro-hardness at Diameter = 50 [mm].

From the same Figs. 7, 8, and 9 it is concluded that as the distance between the machined surface and work piece center increases the chip micro-hardness increases up to 25 mm distance. This observation may be referred to the same reasons previously explained. That is, the cutting forces and shear forces are higher for larger diameters, which in turn generate high machining temperature and resulting plastic deformation to the chip which increases its hardness and because of the variation in the hardness of the chip and the base metal, at the outer surface and toward the center of the work piece.

V. CONCLUSION

1. Low value of chip micro-hardness at high cutting speed (200 m/min) and small work piece diameter (30 mm).

2. High value of chip micro-hardness at high feed rate (0.2mm/rev) and big work piece diameter (50 mm).

3. The interaction effect between cutting speed and feed rate on chip micro-hardness is reported easily, so, chip micro-hardness is higher at high level of feed rate [0.20 mm/rev], but it is better when increasing in cutting speed [200 m/min].

4. Micro-hardness of chips increased at low cutting speed and high feed rate, and large diameter of work piece.

REFERENCES

[1] P. F. Ostwald, J. Munos, Manufacturing Processes and Systems, 9th edition, John Wiley & Sons, Inc. Canada, 1997.
[2] M. P. Groover, Fundamentals of Modern Manufacturing, Prentice-Hall. Inc. USA, 1996.
[3] Jain, V. K., Kumar, S., Kal, Gk., "Effects of machining parameters on the micro-hardness of chips", Vol. 111, August 1989, pp. (220-228).
[4] V. W Clack , R. C Brewer, R. C., "New Technique for Shear zone Thickness Determination in Orthogonal Metal Cutting" Proc. Inst. Of Mech. Engrs., London, Vol. 181, pt. 1, 1966-67, p. 667.
[5] C. R. Hicks, "Fundamental Concepts in the design of experiments, 1973, Holt, Rinehert & Winston Inc., New York.
[6] W. E. Biles, James J. Swain, "Optimization and industrial experimentation", 1980, John Wiley & sons, New York.
[7] G. E. Box, J. S. Hunter, "Multi-factor experiment design for exploring response surface", Annuals of Mathematical Statistics, Volume 28, 1957, pp. 195-241.
[8] V. L. Anderson, R. A. Mclean, "Design of experiment", 1974, Marcel Dekker, Inc., New York.
[9] D. C. Montgomery, "Design and analysis of experiments", 1976, John Wiley & Sons, New York.
[10] W. G. Cochran, Gertruda M. Cox, "Experimental designs", 2nd edition, 1957, John Wiley & Sons, New York.
[11] N. R. Drapar, and H. Smith, "Applied regression analysis", 2nd edition, John Wiley & Sons, New York, 1990.