DESIGN OF AN EXPERIMENTAL APPROACH FOR OPTIMIZATION OF SOME FORM ERRORS

M.A. Shouman* and M. Bou-Zeid**
*Industrial and systems Engineering, Department, Zagazig University
** Mechanical Engineering Department, El-Mokhtar University, Libya

The present study introduces the effect of cutting speed, feed rate, depth of cut, and length to diameter ratio (L/D) on roundness and straightness errors of cylindrical specimens of high carbon steel machined at different specified and recommended ranges of machining conditions on lathe with one end gripped in three jaw chuck while the other end was kept free. Several empirical formulae relating out-of roundness and straightness values with speed, feed , depth of cut , and length to diameter ratio as a predictable parameter are introduced in the current article within the specified ranges of machining parameters. Correlation analyses have been carried out to point out the strength between the calculated values and experimental measured values. General remarks, tendencies, and conclusions have been presented.

تقييم الدراسة الحالية تأثير كل من سرعة القطع ومعدل التغذية وعمق القطع وكذلك النسبة بين طول الشغلة الى قطرها (L/D) على أخطاء الاستدارة والاستقامة للمشغولات الأسطوانية التى يتم تثبيت أحد طرفيها على ظرف المخرطة والطرف الآخر يبقى حرا بدون تثبيت. فى هذا الدراسة تم تصميم أسلوب تجريبى للتحديد الأمثل لكل من أخطاء الاستدارة والاستقامة وذلك من خلال استنباط معادلات رياضية لهذه الأخطاء عند نسب مختلفة (L/D = 0.5,1, 1.5, 2, 2.5) ثم تم استنباط معادلات رياضية عامة يكون فيها L/D عامل من عوامل تحديد هذه الأخطاء بالإضافة الى ظروف الأخطاء المأخوذة فى الاعتبار. أيضا تم تصميم برنامج حاسب آلى يحتوى على المعادلات الرياضية المستنبطة لايجاد قيمة كل من الاستدارة أو الاستقامة عند أى قيمة لأى عنصر من عناصر المتغيرات المستقلة. تم أيضا دراسة قوة الارتباط بين المعادلات المستنبطة والقيم الحقيقية لأخطاء الاستدارة والاستقامة وقد وجد ارتباط قوى بين المعادلات المستنبطة والقيم الحقيقية مما يوضح أن العلاقات المستنبطة ذات أهمية خاصة فى تحديد قيم الأخطاء وبالتالى إضافة بعد جديد للشركات الصناعية فى الحفاظ على مستوى الجودة المطلوب من خلال التحكم فى قيم العناصر المستقلة المستخدمة فى العمليات الصناعية. هذا بالاضافة الى تحديد القيم المثلى للأخطاء وكذلك ظروف التشغيل المصاحبة لها.

Keywords: Design of Experiment for form errors, Optimization of form errors, Quality Parameters control, Machining and form errors, Empirical Analysis

INTRODUCTION

The surface geometry plays a very important role in the performance characteristics of a machine part. It is known that it has an influence on mechanical properties such as wear resistance, fatigue strength, strength of interference fits, and corrosion resistance [1]. There is a growing realization that the geometrical shapes and sizes are important if they are seeked to function correctly. Consequently, the accuracy requirements for machine parts have continuously increased and tend to be specially critical in modern industry. Recently the techniques of form errors for surface topography have gained importance from the point of view of their function to be performed in an assembly . This problem is considered as one of hot areas of research [2]. Venture and Yeralarn [3] have developed efficient algorithms for automated roundness inspection of circular production parts when the out-of-roundness value is measured as the optimal objective function of the minimax problem. The out-of-roundness is defined as the maximum deviation of a given set of sample points, taken from the boundary of the production part, from the so called minimax circle. Zahng *et al.* [4] have proposed a methodology that employs computer simulation to dynamically generate the topography of machined surface during an intermittent turning process. The methodology is based on some mathematical models that characterize the

Alexandria Engineering Journal. Vol. 39, (2000) No. 1, 51-63

intermittent turning process as an alternating sequence of forced and free vibratory motion. Osanna *et al* [5] have introduced an approach in which the roundness measurement is used as an important measure for quality evaluation of production parts. Dawson [6] has introduced a procedure for cylindricty and its measurements. In this procedure, the limitations of current instrumentation and measurement techniques with respect to cylindricty have been analyzed. Khan and Shouman [7,8] have discussed various algorithms for form error's evaluation of engineering components, to check the conformity of components to specifications. Also, they have introduced empirical formulae for predicting roundness for aluminum, copper and brass based on some of machining variables and material hardness. A new measurement and compensation method for the grinding of large cylindrical workpieces to improve form accuracy has been developed by Kotamaki [9]. In that work, the generating mechanism and geometry of the main source of form error, the error motion between the tool and workpiece is discussed. The results indicated that the form accuracy can be in many cases improved. A method for measuring the straightness of travel of the carriage of a single point diamond turning machine has been presented by Campbell [10]. This method measures the slide parallelism to the workhead spindle. The quality of measurements achieved were less than 0.1 micron. An accurate, efficient, and robust algorithm for the minimum zone (MZ) straightness and flatness has been developed by Suen *et al.* [11]. In this algorithm, an interval bias adaptive linear neural network structure together with least mean squares learning algorithm, and an appropriate cost function have been used to carry out the interval regression analysis. Also, an estimation procedure of sphericity by means of statistical processing for roundness of spherical parts has been introduces by Kanada [12]. In this procedure, a three-dimensional deviation value from spherical form is calculated from a few two-dimensional roundness values obtained using a general roundness measuring system with a statistical technique.

PROBLEM FEATURE

Numerous parameters affect the geometry of the machined surfaces. The formation of micro-, and macro-irregularities on the surface of machined components depends on the following principle factors [13]: 1-Cutting conditions (cutting speed, feed rate, and depth of cut).2-Workpiece size. 3- Workpiece material. 4-Cutting tools(type, form, material, and sharpness). 5-Machine condition. 6-System rigidity. 7-Machining operation. 8-Character and type of applied coolant. In the current work, the cutting conditions and workpiece size are under consideration while the other factors are held constant. As a matter of fact, the cutting conditions play a very important role in the performance characteristics of the form errors of a machined part. The size of the workpiece to be machined to some extent affects the desired accuracy of form. As it is mentioned in [2,14,15], higher "L/D" ratios tends to elevate the central hump in the system deflection while lower "$L/D \leq 3$" ratio is not as harmful as a higher "$L/D>5$"as regard the accuracy of turned cylindrical surfaces. In principle the major aims of any machining process is the production of workpieces within the imposed tolerance of form, dimensions, surface finish and quality. The form errors of two dimensional surfaces like roundness and straightness are important from the functional point of view in an assembly, where the ability of slides to move along straight lines and rotating parts to rotate about a fixed axis is essential. Since most of the functional components are round and straight, the measurement and evaluation of such components are needed to clarify the influence of common cutting parameters and workpiece size on surface geometry. In the current investigations, an attempt has been done to study the degree to which the machining parameters (cutting speed, feed rate, and depth of cut) and component size

(L/D = .5, 1, 1.5, 2, 2.5) affect roundness and straightness errors.

EXPERIMENTAL WORK

Experimental investigations were performed on specimens of high carbon steel SEA 1095 having hardness of 210HB. In accordance within the machine static and dynamic tests, some recommended tests have been done on the used machine (Harrison 600). The vibration displacements of the machine spindle are measured for loading and unloading conditions. The measured parameters for static and dynamic tests were found within the permissible values of standard tests that are advised by Schlesnger [16] . A single point tool of high speed steel having square crossectional area of 12.7* 12.7 mm and right hand turning with standard geometry presentation of 0,10,8,8,8,15,1 has been used in the current work [17]. The tool was set on the lathe and applied with more rigid supporting method and minimum overhang of 20 mm. Also the tool was mounted on-center so that the effective cutting angles are the same as those ground on the tool, and applied with the cutting edge inclined to the direction of feed (oblique cutting) [18]. The tool life was taken into consideration where each cutting edge was used according to the predicted tool life. In this aspect and in order to minimize the effect of tool wear on the resulted form errors, the standards of flank wear criterion [19,20] for HSS are used. A coolant of soluble oil as an emulsion with water (1:3) has been used as a cutting fluid and applied at the cutting edge. In the current study, the interest is focused on cutting speed (V), feed rate (f), depth of cut (d), length to diameter ratio (L/D), and their interactive influence on roundness and straightness errors. This attention is highlighted for cylindrical specimens with one end gripped in a three-jaw chuck and the other end was kept free. A three variables, three factorial design for each fixed length to diameter ratio (.5, 1, 1.5, 2, 2.5) were performed. The choice of high, medium and low levels for variables are shown in Table 1. The values fall within practical and recommended limits of machining conditions and provide a range which enable possible effects to be detected [19]. The measured responses are out-of-roundness and straightness values.

Table 1 Three levels of cutting variable

Variable		Unit	Low	Medium	High
Cutting speed	V	m/min.	12	21	30
Feed rate	f	mm/rev	0.05	0.1	0.2
Depth of cut	d	mm	0.1	0.3	0.5

According to the cited experimental strategy, 135 test specimens have been machined. This number of test specimens have been divided into three groups. Each group has been made up of 45 test specimens. The first group was machined at cutting speed 12m/min. and 45mm diameter. Second and third group were machined to be 37mm in diameter and at cutting speed 21 and 30 m/min. respectively. Each group consists of five sets with respect to the fixed L/D ratios (.5,1,1.5,2,2.5). Each set contains nine test specimens to comprise all possible combinations of feeds and depth of cuts under consideration. The out-of-roundness was measured for all specimens using Talyrond 200 system and minimum-zone-center approach (MZA, Figure 1).

Because the roundness measurement of a certain plane represents only the out-of-roundness for the measured plane [21], and the maximum error is more important from the manufacturing point of view. Measurements for the designed workpiece structure have been taken for 28 specimens that expected to provide maximum errors, to see the trend of variation of the error along the machined length. The measurements were carried out at five planes (0,L/4,L/2,3L/4,L) along the machined length of the specified specimens. The data obtained were fitted into trends (using statistical software) and the plane of maximum value was found at plane L; i.e. at the free end of the machined length. Also, straightness measurements were carried out on four generating lines for each specimen. The straightness value of each specimen is the mean value of the measured generators (Figures 2,3). However, Table 2 lists the measurements of out-of-roundness. Table 3 presents straightness measurements.

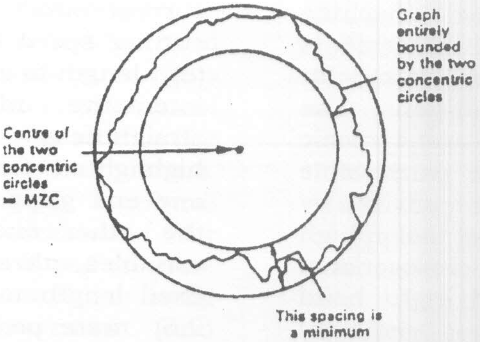


Figure 1 Conditions for minimum zone center

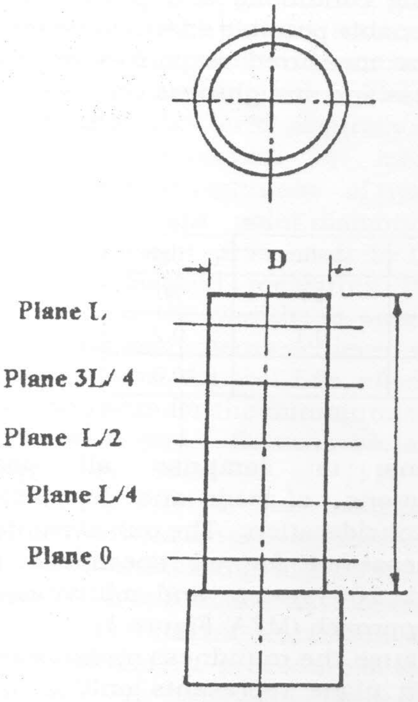


Figure 2 Five planes along the machined length of out-of-roundness measurement

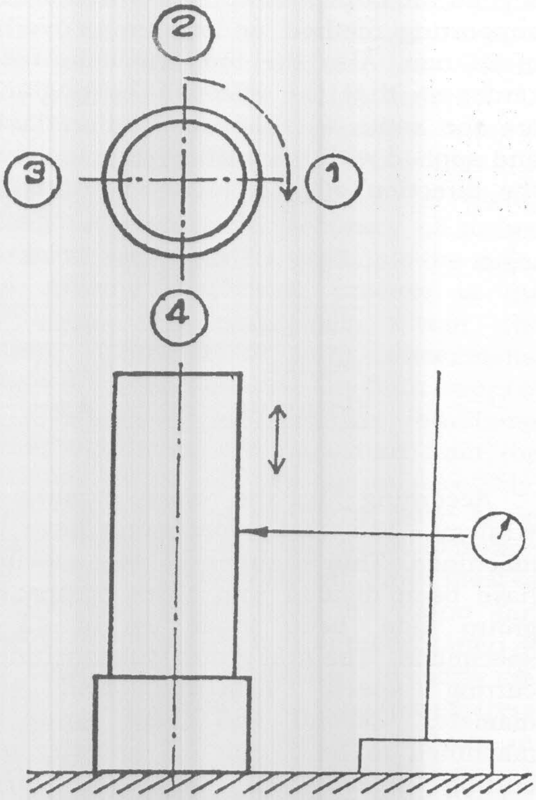


Figure 3 Measured generating lines for straightens error

***Table* 2** Out-of-roundness values (μm)

L/D	f	V = 12 m / min			V = 21 m / min			V = 30 m / min		
		depth of cut			depth of cut			depth of cut		
		0.1	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**	**0.1**	**0.3**	**0.5**
1/2	0.05	3.75	2.75	3.50	3.75	3.25	3.75	3.25	2.25	2.00
	0.10	5.00	10.00	5.00	5.00	4.50	3.75	5.50	2.00	2.25
	0.20	10.00	12.00	6.50	6.25	2.25	3.50	3.00	3.50	3.50
1	0.05	4.50	5.75	4.25	3.25	2.00	3.50	2.50	3.00	2.75
	0.10	14.00	6.00	10.00	3.75	3.00	4.25	4.75	3.50	3.50
	0.20	10.00	14.00	9.00	7.25	3.50	4.25	5.25	3.50	4.75
3/2	0.05	5.25	5.25	4.50	3.75	2.75	4.00	3.50	3.75	2.50
	0.10	13.00	8.00	6.50	6.00	5.00	4.00	3.00	4.00	3.75
	0.20	13.00	9.00	8.50	7.00	5.25	4.25	4.00	5.75	4.25
2	0.05	4.50	6.00	6.75	5.75	6.50	10.00	3.00	3.00	2.25
	0.10	9.00	5.50	6.50	5.75	3.25	5.25	3.25	3.00	4.50
	0.20	14.00	14.50	9.00	4.50	6.00	6.25	4.75	4.00	4.00
5/2	0.05	6.50	5.25	5.25	5.00	2.25	3.25	3.75	2.75	2.75
	0.10	6.00	15.00	13.50	4.00	4.75	3.25	6.50	5.25	8.50
	0.20	14.00	17.00	12.00	8.25	7.50	4.50	5.50	9.25	5.50

***Table* 3** Straightness values (μm)

L/D	f	V = 12 m / min			V = 21 m /min			V = 30 m / min		
		depth of cut			depth of cut			depth of cut		
		0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
½	0.05	4.00	7.84	3.55	10.25	2.24	3.21	2.58	2.12	2.35
	0.10	8.81	2.50	3.37	2.90	3.78	3.52	2.37	3.79	3.00
	0.20	4.50	6.25	4.00	3.28	3.10	4.46	2.90	3.03	2.75
1	0.05	10.06	18.86	6.00	6.47	3.62	4.09	3.68	2.75	1.87
	0.10	10.50	5.12	6.69	5.03	4.12	4.00	2.87	2.12	2.43
	0.20	6.62	13.31	7.81	4.90	4.53	5.59	3.75	3.90	2.24
3/2	0.05	11.00	25.65	6.84	19.19	3.77	5.53	3.87	4.03	3.68
	0.10	11.69	7.12	5.18	5.53	5.65	4.12	3.50	4.56	5.53
	0.20	10.28	6.43	6.56	5.34	4.31	5.78	4.15	4.00	4.25
2	0.05	12.00	13.06	7.78	16.65	4.62	6.65	4.52	4.40	3.40
	0.10	5.22	5.50	5.15	4.78	4.12	5.03	3.77	4.09	4.62
	0.20	10.12	6.95	9.50	5.43	6.09	5.00	4.28	4.09	4.25
5/2	0.05	15.00	9.44	8.00	29.12	4.69	4.16	4.75	4.75	3.00
	0.10	9.62	12.12	10.31	6.03	5.12	6.09	3.72	5.56	3.67
	0.20	12.87	14.19	10.25	4.69	4.00	4.94	5.62	5.28	4.87

MATHEMATICAL MODEL

A full factorial design is used in experiments involving several factors at several levels. The number N of all possible combinations to be performed during the experiment is given by:

$$N = n^k \qquad (1)$$

Where n is the number of levels and k is the number of factors. Response surface methodology has been applied where it is recommended as one of the best experimental designs for quantifying empirical relations for surface geometry characteristics [22]. Also one of its main privileges is that the number of experimental tests is reduced. The influence of cutting speed, feed rate, and depth of cut on the surface geometry characteristics is determined through a 2^3 factorial design for each fixed length to diameter ratio. To determine the influence of the parameter L/D ratio with the cutting conditions on the surface geometry, a stepwise of 2^4 factorial design is employed. To find a suitable approximation for the true functional relationship between the considered responses and the independent variables, low and high order equations were tested. A functional relationship between the surface characteristics and the independent variables under investigation can be postulated as

$$P_i = C * V^{\alpha} * F^{\beta} * d^{\gamma} * (L/D)^{\varepsilon} \qquad (2)$$

Where P_i is dependent response variable; V,F, d and (L/D) are independent variables; C is constant; $\alpha,\beta,\gamma,\varepsilon$ are exponents. In the current work, the response variable P_i is either out-of-roundness or straightness error in micron while the independent variables are cutting speed, feed, depth of cut, and length to diameter ratio. The above equation can be simplified in general from for j=1,2,3...k factors as

$$Y_i = b_o + b_1 Z_1 + b_2 Z_2 + \ldots + b_j Z_j \quad (j = 1,2,3\ldots k) \qquad (3)$$

Generally for any factor Z_i we have

$$Z^o_j = (Z^{max}{}_j + Z^{min}{}_j)/2 \qquad (j = 1,2,3\ldots\ldots k) \qquad (4)$$

$$\Delta\, Z_j = (Z^{max}{}_j - Z^{min}{}_j)/\,2 \qquad (j = 1,2,3\ldots\ldots k) \qquad (5)$$

The point with the coordinates $(Z^{\circ}_1, Z^{\circ}_2, .., Z^{\circ}_k)$ is called the center point of design, or basic level, and $\Delta\, Z$ is the unit or interval of variation on the Z -axis. In order to pass from the Z_1, Z_k coordinates to a dimensionless system of coordinates $X_1, X_2, \ldots X_k$, the following coding equation should be used:

$$X_j = (Z_j - Z^o_j)/\Delta\, Z_j \quad (j = 1, 2, 3, \ldots\, k) \qquad (6)$$

In dimensionless coordinates system, the upper and lower levels are at +1 and -1 respectively. The coordinates of center point of the design are zero and coincide with the origin of coordinates. Tables 4 and 5. list the values of variable levels considered in natural scale and coding system for 2^3 and 2^4 factorial designs respectively.

Table 4 Variable levels in natural scale

Variable	Unit	Low	Medium	High
V	m/min	12.00	21.00	30.00
F	mm/rev	0.05	0.10	0.20
d	mm	0.10	0.30	0.50
L/D	-	1/2	3/2	5/2

Table 5 Coding table for factorial designs

	2^3 Factorial design			2^4 Factorial design		
	Low	Medium	High	Low	Medium	High
V	-1	0	+1	-1	0	+1
F	-1	0	+1	-1	0	+1
d	-1	0	+1	-1	0	+1
L/D	-1	0	+1	-1	0	+1

Based upon the above transformation, both the transformed equation and the experimental matrix will be given in general form as:

$$y_i = x_o\, b_o + b_1\, x_1 + x_2\, b_2 + \ldots + b_j\, x_j$$
$$(j = 0,1,2,3,..k) \qquad (7)$$

Where x_o is a dummy variable equal to unity.

Any coefficient b_j of the estimated regression is defined by a scalar product of y_i column by the respective x_j column divided by the number of experiment N, where the mathematical replica is expressed as

$$b_j = (1/N) \sum_{i=1}^{N} x_{ji}\, y_i \quad (j = 0,1,2,..k), (i = 0,1,2,..N) \qquad (8)$$

Table 6 Experimental matrix in general form

No.	x_o	X_1	X_2	...	Xj	Y_i
1	X_{o1}	X_{11}	X_{21}		X_{j1}	Y_1
2	X_{o2}	X_{12}	X_{22}		Y_{j2}	Y_2
.	.	.	.		.	
.	.	.	.		.	
		.	.			
N	X_{oi}	X_{1i}	X_{2i}		X_{ji}	Y_i

The experimental matrices in coded form for 2^3 and 2^4 factorial designs with four measurements at the center point of each design can be deduced by the aids of Table 5. The addition of center points ($x_j=0, j=1,2,\ldots,k$) to the 2^k design does not influence the $\{b_j\}$ for $j \geq 1$, but the estimate of b_o becomes the grand average of all measurements. Furthermore, the addition of center points does not alter the orthogonality property of the design [22].

Correlation analyses have been carried out to determine the strength of correlation between the calculated values of response variables and the experimental measured values. Based upon the previous transformation, experimental matrices, and measured values of out-of-roundness and straightness errors; both the mathematical formulae of the response variable (out-of-roundness and straightness error) and correlation coefficients can be derived. Table 7. presents the obtained values of the derived formulae for the constant (C), exponents (α, β, γ, ε), and the corresponding correlation coefficient (CC).

Table 7 Exponents, constant, and correlation coefficient for empirical relations

RV	L/D	C	α	β	γ	ε	CC
RV1	1/2	97.58	-0.789446	0.441315	-0.071983	-	0.92
	1	87.15	-0.629316	0.511670	-0.025987	-	0.95
	3/2	105.03	-0.781701	0.397980	-0.132792	-	0.93
	2	179.90	-0.926542	0.443188	-0.077030	-	0.91
	5/2	161.19	-0.794270	0.481513	-0.105298	-	0.97
GRV1	1/2 - 5/2	123.41	-0.791858	0.461421	-0.088639	0.294550	0.97
RV2	1/2	14.18	-0.454305	0.092193	-0.059588	-	0.92
	1	76.85	-1.088285	0.008036	-0.239796	-	0.90
	3/2	53.69	-0.820068	0.018822	-0.147697	-	0.93
	2	80.06	-0.946509	0.035694	-0.122457	-	0.92
	5/2	120.29	-1.010454	0.134774	-0.226631	-	0.93
GRV2	1/2 - 5/2	42.40	-0.732382	0.113484	-0.143110	0.482599	0.93

RV : Response variable RV1: Out-of-roundness RV2 : Straightness error
GRV1 : Out-of-roundness by general formula GVR2 : Straightness error by general formula

RESULTS AND DISCUSSION

Based on the applied design of an experimental approach, empirical formulae for predicting out-of-roundness and straightness error have been developed. The remarks and tendencies are being presented in the following paragraphs:

1. For each length to diameter ratio, the out-of-roundness were measured at different crossections of the machined length. The maximum roundness error was found at the free end. The presence of maximum out-of-roundness at the free end of the machined specimen is due to the resistance of workspecimen to the system of cutting force is very week at that point, while it is very strong at the gripped end. The maximum deflection during the cutting process is the main source of maximum out-of-roundness at the free end (Interactive effect of machining and beam deflection of cantilever fixation) [23].
2. Specified and general empirical formulae have been developed for predicting out-of-roundness and straightness error. These empirical relations have been tested and compared to the actual experimental values of out-of-roundness (ARV1) and straightness (ARV2). A sample of this comparison is presented through Figures 4 to 15. Figures 4 to 8 present both ARV1 and RV1 for the considered L/D (0.5,1,1.5,2,2.5) respectively, while Figure 9 presents ARV1, RV1, and GRV1 at L/D =1.5. These Figures are presented at different cutting speeds of the considered range and at the specified feeds and depth of cuts. In all Figures both RV1 and GRV1 are fitted into trends to compare

them with ARV1. The same system approach have been applied for straightness presentation in Figures 10 to 15. The exhibited data in these figures shows that the derived empirical formulae for each specified L/D or general formula are very sensitive in predicting and evaluation of both the out-of-roundness and straightness error where the plotted predicted response variable in most cases is very close to the actual value or equal to it. This higher sensitivity indicates that, the designed approach, experimental procedure, measurement system, and evaluation method (response surface methodology) are applied in reliable and confidence way. As a matter of fact, the applied procedure of investigation affects the strength of correlation's between the response variable and independent variables. However, the minimum strength of correlation of the derived formulae was found to be 90% for straightness equation at L/D = 1, while the maximum strength of correlation of the derived formulae was found to be 97% for out-of-roundness equation at L/D=5/2 and for general out-of-roundness equation.

3. A study for determining the maximum (m2) and minimum (m1) values of response variable(out-of-roundness or straightness error) has been carried out using the derived empirical relations for either any specified length to diameter ratio or any machining variables. These maximum and minimum values are evaluated upon the levels of machining variables in natural scale and the signs of the corresponding exponents. These values are listed in Tables 8 to 11. This study is utilized in determining both the local optimum values (m1) or general optimum values (Gm1) of response variable (RV1 or RV2) . These optimum values have been presented for the considered and recommended ranges of variations. By the aids of these optimum values, the independent variables (V,f,d, L/D) are become controllable variables for the achievement of optimal condition of response variables and within the limited ranges (with respect to the available) of machining variables under consideration.
4. A computer software has been designed and created for constructing predictable tables for response variable (RV1 and RV2) based on the considered ranges of variations for machining variables and length to diameter ratios. This software is capable for evaluation the response variables at any input independent variables. However, Tables 12 and 13 present a sample of these predictable tables.

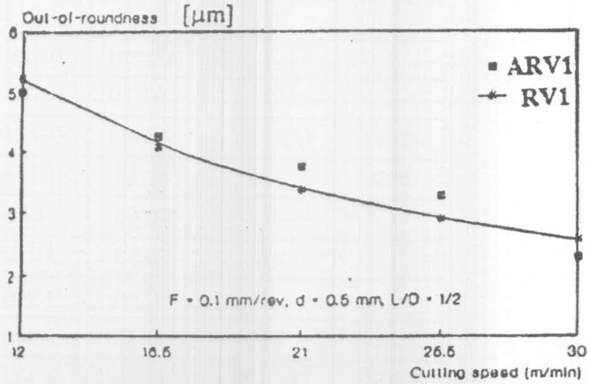


Figure 4 Out-of-roundness versus cutting speed

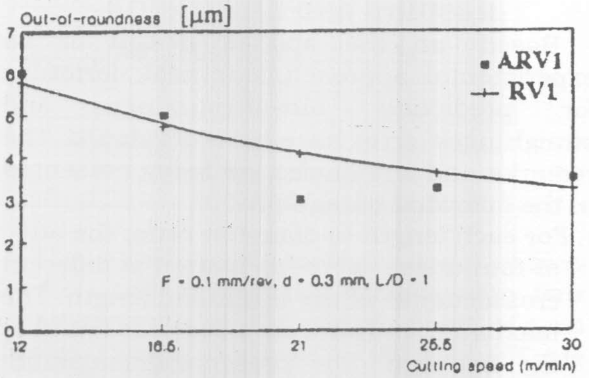


Figure 5 Out-of-roundness versus cutting speed

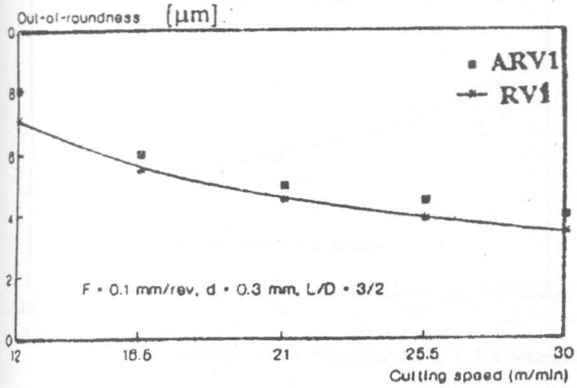


Figure 6 Out-of-roundness versus cutting speed

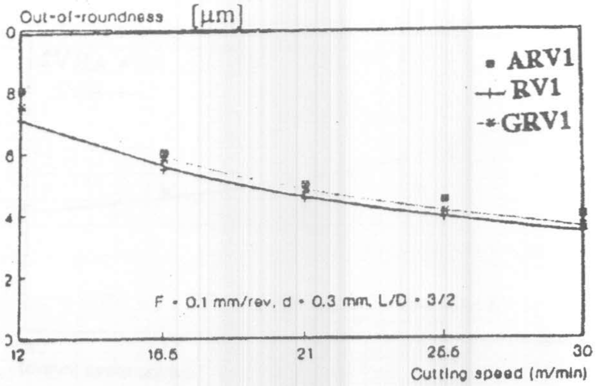


Figure 9 Out-of-roundness versus cutting speed

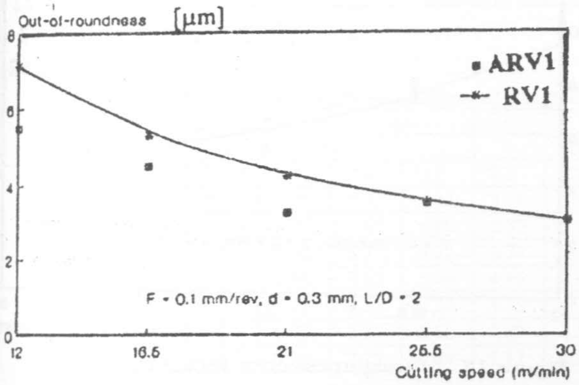


Figure 7 Out-of-roundness versus cutting speed

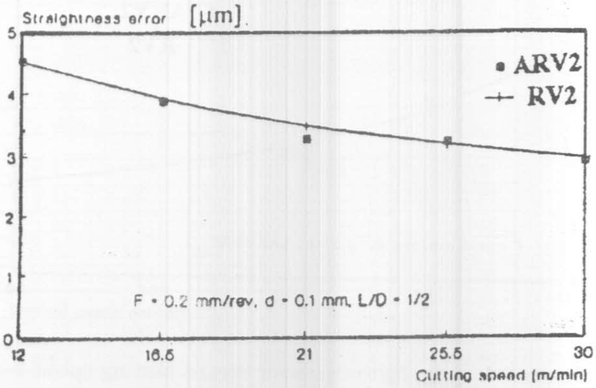


Figure 10 Straightness error versus cutting speed

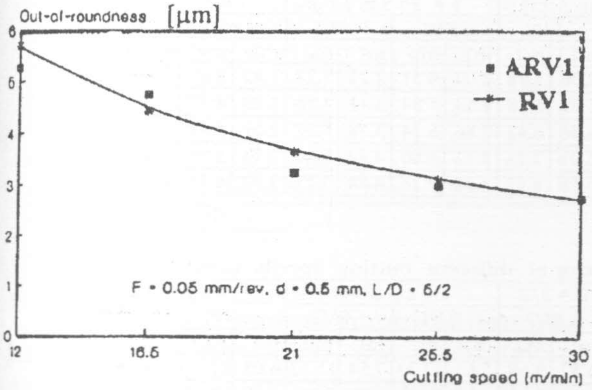


Figure 8 Out-of-roundness versus cutting speed

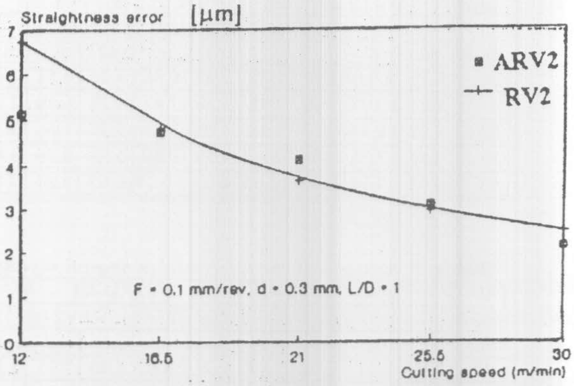


Figure 11 Straightness error versus cutting speed

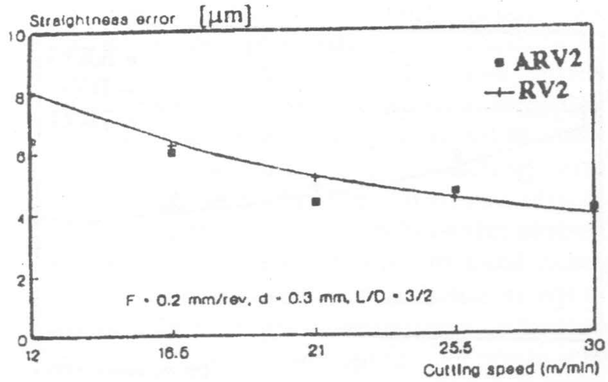


Figure 12 Straightness error versus cutting speed

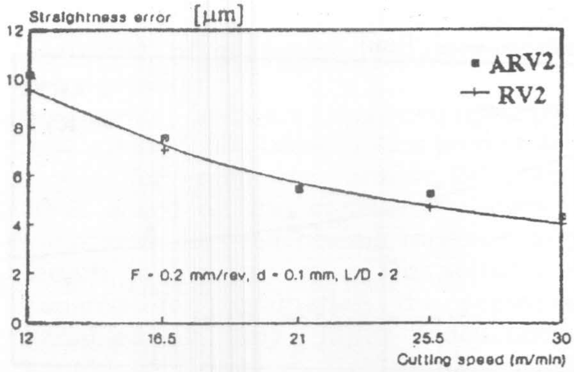
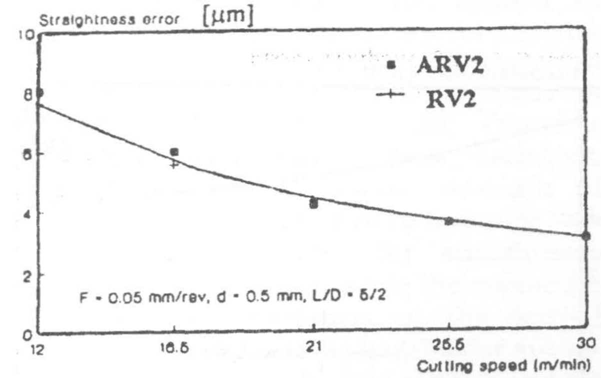


Figure 13 Straightness error versus cutting speed

Figure 12 Straightness error versus cutting speed



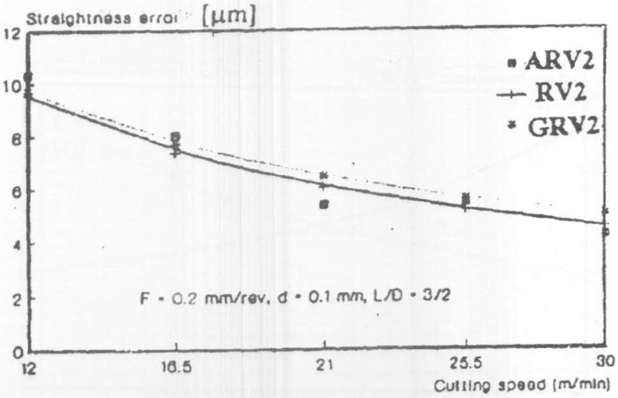


Figure 14 Straightness error versus cutting speed

Figure 15 Straightness error versus cutting speed

Table 8 Ranges of out-of-roundness and straightness error at different "L/D" ratios (µm).

L/D	V = 12 m / min				V = 16.5 m / min				V = 21 m / min				V = 25.5 m / min				V = 30 m / min			
	RV1		RV2		RV1		RV2		RV1		RV2		RV1		RV2		RV1		RV2	
Ratio	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2
1/2	3.75	8.21	3.86	5.69	2.92	6.38	3.06	4.51	2.41	5.27	2.56	3.78	2.07	4.51	2.22	3.28	1.82	3.97	1.97	2.91
1	4.6	10.07	5.40	7.95	3.58	7.82	4.28	6.30	2.96	6.46	3.58	5.28	2.53	5.54	3.11	4.58	2.23	4.87	2.76	4.07
3/2	5.19	11.34	6.57	9.68	4.03	8.81	5.20	7.66	3.33	7.28	4.36	6.42	2.86	6.24	3.78	5.57	2.51	5.49	3.36	4.95
2	5.65	12.35	7.54	11.12	4.39	9.59	5.98	8.80	3.62	7.93	5.01	7.38	3.11	6.80	4.34	6.40	2.73	5.98	3.86	5.68
5/2	6.03	13.19	8.40	12.38	4.69	10.25	6.65	9.81	3.87	8.47	5.58	8.22	3.32	7.26	4.84	7.13	2.92	6.38	4.29	6.33

optimum

Table 9 Ranges of out-of-roundness and straightness error at different cutting speeds (µm).

V m/ min	L / D = ½				L / D = 1				L / D = 3/2				L / D = 2				L / D = 5/2			
	RV1		RV2		RV1		RV2		RV1		RV2		R V1		RV2		RV1		R V2	
	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2
12	3.75	8.21	3.86	5.69	4.60	10.07	5.40	7.95	5.19	11.34	6.57	9.68	5.65	12.35	7.54	11.12	6.03	11.19	8.40	12.38
16.5	2.92	6.38	3.06	4.51	3.58	7.82	4.28	6.30	4.03	8.81	5.20	7.66	4.39	9.59	5.98	8.80	4.69	10.25	6.65	9.81
21	2.41	5.27	2.56	3.42	2.96	6.46	3.58	5.28	3.33	7.28	4.36	6.42	3.62	7.93	5.01	7.38	3.87	8.47	5.58	8.22
25.5	2.07	4.51	2.22	3.28	2.53	5.54	3.11	4.58	2.86	6.24	3.78	5.57	3.11	6.80	4.34	6.40	3.32	7.26	4.84	7.13
30	1.82	3.97	1.97	2.91	2.23	4.87	2.76	4.07	2.51	5.49	3.36	4.95	2.73	5.98	3.86	5.68	2.92	6.38	4.29	6.33

optimum

Table 10 Ranges of out-of-roundness and straightness error at different feed rates (μ m)

f	L / D = 1/2				L / D = 1				L / D = 3/2				L / D = 2				L / D = 5/2			
mm/	RV1		RV2		RV1		RV2		RV1		RV2		RV1		RV2		RV1		RV2	
rev	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2
0.05	2.09	4.33	2.49	4.87	2.57	5.31	3.47	6.79	2.89	5.98	4.23	8.27	3.15	6.51	4.86	9.50	3.37	6.95	5.41	10.58
0.075	2.53	5.22	2.60	5.09	3.10	6.40	3.64	7.12	3.49	7.21	4.42	8.66	3.80	7.85	5.08	9.95	4.06	8.39	5.66	11.08
010	2.88	5.96	2.69	5.26	3.54	7.31	3.75	7.35	3.99	8.23	4.57	8.94	4.34	8.97	5.25	10.28	4.63	9.58	5.85	11.45
0.15	3.47	7.19	2.82	5.51	4.27	8.81	3.94	7.70	4.81	9.93	4.79	9.37	5.23	10.81	5.50	10.76	5.39	11.55	6.13	11.98
0.20	3.97	8.21	2.91	5.69	4.87	10.07	4.07	7.95	5.49	11.34	4.95	9.68	5.98	12.35	5.68	11.12	6.38	13.19	6.33	12.38

optimum

Table 11 Ranges of out-of-roundness and straightness error at different depth of cut (μm).

d	V = 12 m / min				V = 16.5 m / min				V = 21 m / min				V = 25.5 m / min				V = 30 m / min			
	R V 1		RV2		RV1		RV2		RV1		RV2		RV1		RV2		RV1		RV2	
mm	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2	m1	m2
0.1	2.09	8.21	2.49	5.60	2.57	10.1	3.47	7.95	2.89	11.3	4.23	9.68	3.15	12.4	4.86	11.1	3.37	13.2	5.41	12.4
0.2	1.97	7.72	2.25	5.15	2.42	9.47	3.15	7.21	2.72	10.7	3.83	8.76	2.96	11.6	4.40	10.1	3.17	12.4	4.90	11.2
0.3	1.90	7.45	2.12	4.86	2.33	9.13	2.97	6.80	2.63	10.3	3.61	8.27	2.86	11.2	4.15	9.50	3.05	12	4.62	10.6
0.4	1.85	7.26	2.04	4.67	2.27	8.90	2.85	6.52	2.56	10	3.47	7.94	2.79	10.9	3.89	9.12	2.98	11.7	4.43	10.2
0.5	1.82	7.12	1.97	4.52	2.23	8.73	2.76	6.32	2.51	9.84	3.36	7.69	2.73	10.7	3.86	8.83	2.92	11.4	4.29	9.83

optimum

Table 12 Predictable out-of-roundness at length to diameter ratio 1/2 (μm)

L/D =1/2	V = 12 m / min					V = 21 m / min					V = 30 m / min				
	depth of cut					depth of cut					depth of cut				
f	0.1	0.2	0.3	0.4	0.5	0.1	0.2	0.3	0.4	0.5	0.1	0.2	0.3	0.4	0.5
0.05	4.32	4.11	3.99	3.91	3.85	2.78	2.64	2.56	2.51	2.47	2.09	1.99	1.94	1.90	1.87
0.07	5.16	4.91	4.77	4.67	4.60	3.32	3.16	3.07	3.00	2.96	2.59	2.38	2.31	2.27	2.23
0.10	5.86	5.58	5.42	5.31	5.22	3.77	3.59	3.48	3.41	3.36	2.84	2.71	2.63	2.57	2.53
0.12	6.47	6.15	5.98	5.85	5.76	4.16	3.96	3.84	3.76	3.70	3.14	2.99	2.90	2.84	2.79
0.15	7.01	6.70	6.48	6.35	6.24	4.51	4.29	4.16	4.08	4.01	3.40	3.24	3.14	3.08	3.03
0.17	7.50	7.14	6.93	6.79	6.68	4.82	4.59	4.46	4.37	4.30	3.64	3.46	3.36	3.29	3.24
0.20	7.96	7.57	7.35	7.20	7.09	5.12	4.87	4.73	4.63	4.56	3.86	3.67	3.57	3.49	3.44

Table 13 Predictable straightness error at length to diameter ratio 3/2 (μm)

L/D =3/2	V = 12 m / min					V = 21 m / min					V = 30 m / min				
	depth of cut					depth of cut					depth of cut				
f	0.1	0.2	0.3	0.4	0.5	0.1	0.2	0.3	0.4	0.5	0.1	0.2	0.3	0.4	0.5
0.05	9.29	8.39	7.90	7.57	7.33	5.87	5.30	4.99	4.78	4.63	4.38	3.96	3.73	3.57	3.46
0.07	9.36	8.45	7.96	7.63	7.38	5.92	5.34	5.03	4.82	4.67	4.42	3.99	3.75	3.60	3.48
0.10	9.41	8.50	8.00	7.67	7.42	5.95	5.37	5.06	4.85	4.69	4.44	4.01	3.78	3.62	3.50
0.12	9.45	8.53	8.04	7.70	7.45	5.97	5.39	5.08	4.86	4.71	4.46	4.03	3.79	3.63	3.52
0.15	9.49	8.56	8.07	7.73	7.48	5.99	5.41	5.10	4.88	4.73	4.47	4.04	3.80	3.65	3.53
0.17	9.51	8.59	8.09	7.75	7.50	6.01	5.43	5.11	4.90	4.74	4.49	4.05	3.82	3.66	3.54
0.20	9.54	8.61	8.11	7.77	7.52	6.03	5.44	5.12	4.91	4.75	4.50	4.06	3.83	3.67	3.55

CONCLUSION

Specified and general empirical formulae have been developed for the evaluation of out-of-roundness and straightness errors. These empirical relations are very sensitive in evaluating and predicting the response variables under consideration. The derived formulae are utilized in determining both the local optimum response variable (m1 of RV1 and RV2 for all the considered ranges of variations of dependent variables V,f,d L/D) and general optimum response variable (Gm1 of RV1 and RV and for each specified range of variation of the dependent variable). The maximum evaluated error of response variable (local m2 or m2 at optimum condition) can be determined by the developed formulae. Moreover, the response variable can be evaluated at any input value of the independent variables. Also, one of the main contribution of the current study is that, for the considered machining ranges

(V =12-30 m/min, f= .05-.2 mm/rev, d= .1-.5 mm, L/D= .5-2.5), the independent variables are become controllable variables for optimality achievement of response variable or at least to obtain production parts within the imposed quality tolerances of out-of-roundness and/or straightness.

ACKNOWLEDGMENT

The principal author wishes to express his great thanks and pleasure to Associate Professor Mohammed A. Younes for his valuable advice in presenting the current work .

REFERENCES

1. B. Velsher, M.O.M. Osman and T. S. Sanker, "Stochastic Characterization of Macro- and Micro-errors of Journal Bearing Roundness" ASME, Vol. 199, No. 2, p. 327-337, (1977).
2. C.H. Kahng, H.W. Lord and T.L. Davis, 1976, "The effect of Chucking Methods on Roundness Error in the Boring Process", ASME, Vol. 90, No. 1, p. 223-238, (1976).
3. J.A. Venture and S. Yeralen, "The Minimax Center Estimation Problem for Automated Roundness Inspection", EJOR, Vol. 41, No. 1, pp. 64-72, (1991).
4. G.M. Zhang, S. Yarramaredy, S.M. Lee and S.C. Lu, "Simulation of Surface Topography Formed During the Intermittent Turning Process", ASME, Vol. 113, pp. 273-279, (1991).
5. P.H. Osanna, N.M. Durakbass and R. Oberlander, "Cylindricity - A Well Known Problem and New Solutions", International Journal of Machine Tools Manufacturing, Vol. 32, No. 1/2, pp. 91-97, (1992).
6. J.W. Dawson, "Cylindricity and its Measurements". International Journal of Machine Tools Manufacturing, Vol. 32, No. 1/2, pp. 247-253,1992.
7. M.I. Khan and M.A. Shouman, "Algorithms for Form Error Evaluation", AMSE, Vol. 48, No. 4, p. 29-44, (1993).
8. M.A. Shouman and M.I. Khan, "Effect of Cutting Parameters on the Roundness of Turned Components", AMSE, Vol. 63, No. 3, p. 9-26, (1996).
9. M.J. Kotamaki, "In-Situ Measurement and Compensation Control in External Grinding of Large Cylinder", ACTA-POLTECH-SCAND MECH-ENG-SER., No. 121, pp. 2-123, (1996).
10. A. Cambell, "Measurement of Lathe Zslide Straightness and Parallelism Using Flat Land", PRECIS-Eng., Vol. 17, No. 3, p. 207-210, (1995).
11. D.S. Suen and C.N. Chang, "Application of Neural Network Interval Regression Method for Minimum Zone Straightness and Flatness", Journal of American Society for Precision Engineering, Vol. 20, No. 3, p. 196-207, (1997).
12. T. Kanada, "Estimation of Sphericity by Means of Statistical Processing for Roundness of Spherical Parts", Journal of American Society for Precision Engineering, Vol. 20, No. 2, pp. 117-137, (1997).
13. D. Maslov, V. Danilevsky and V. Sasov, Engineering Manufacture Process in Machine and Assembly Shops, Mir Publishers, Moscow, Third Edition, (1976).
14. S. Bajpai, "Optimization of Workpiece Size for turning Accurate Cylindrical Parts", International Journal of Machine Tool Design and Research, Vol. 12, pp. 221-228, (1972).
15. A. Tantawy, Machine Tools, Helwan University Press, Egypt, (1981).
16. G. Schlesnger, "Testing Machine Tools", Eighth Edition, Pergamon Press (1978).
17. F.W. Wilson and P.D. Harvey, Tool Engineering Handbook, Second Edition, McGraw-Hill, (1959).
18. R.L. Timings, Basic Engineering Craft Course Workshop Theory, Fifth Edition, Longman, London Ltd., (1978).
19. P.C. Pandy and C.K. Singh, Production Engineering Science, Fifth Edition, New Chand Jain, (1984).
20. F.W. Wilson and P.D. Harvey, Tool Engineering Handbook, Second Edition, McGraw-Hill, (1959).

21. Annon, Talyrond 200, Operations Handbook, Rank, Second Edition, Talyor Hobson Ltd., (1984).
22. D.C. Montgomery, Design and Analysis of Experiments, Third edition, John Wiley and Sons, Inc., (1991).
23. J.W. Case and A.H. Chilver, Strength of Materials and Structure, Second Edition, Edward Arnold Ltd., 1971.

Received September 24. 1998
Accepted November 28. 1999