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Performance Evaluation of Rotary EDM by Experimental Design Technique

J.S. Soni
Defence Research & Development Laboratory, Hyderabad - 500 058.

and

G. Chakraverti
J.N.T.U. College of Engineering, Hyderabad - 500 072.

ABSTRACT

This paper presents an experimental design to study the performance of rotary electro-discharge machining (EDM). Scientific investigations have been carried out to find the effect of various EDM parameters. Titanium alloy and die steel workpieces were machined with copper-tungsten tool electrode. The response surface technique has been adopted to compare the performance of rotary EDM, since such technological surfaces serve as an objective criteria to compare EDM systems. Moreover, such a surface and its response function serve as a mathematical model of the process. The analysis of the results was based on standard statistical techniques. The response surfaces and the corresponding response functions were determined for the machining indices for metal removal rate, surface finish, micro-hardness, etc. All the calculations were carried out through a computer programme specially developed for this purpose.

1. INTRODUCTION

It is difficult to formulate a mathematical model for the complex production system, such as electro-discharge machining (EDM), by the existing methods of science and engineering. However, huge amount of accurately recorded data can be obtained for most of the variables of importance which control productivity of the process. The systematic and quantitative analysis of the observed data could lead to the equation governing the system performance which can be used to formulate its mathematical model[1].

A limited number of experiments were conducted to study the effects of various machining parameters on EDM process. Studies were undertaken to investigate the effects of pulse current, pulse duration and electrode rotation on metal removal rate, electrode wear rate, relative electrode wear, surface finish (Ra), overcut, and out of roundness. Experiments were also conducted for through and blind-holes machining. An attempt was also made to compare the results with stationary electrodes. Titanium alloy and die steel workpieces were electro-discharge machined with copper-tungsten tool electrode. A study on surface texture, debris and crater formation, cracking

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characteristics, surface micro-hardness and migration of material from either of the electrodes was also conducted.

The analysis of the results was based on standard statistical techniques. The response surfaces and the corresponding response functions were determined for the above machining indices. The model for the experiments was planned on the basis of cybernetic black box system. A 3^2 factorial design was chosen for the experimental work.

2. EXPERIMENTAL SETUP

2.1 Work Materials

High-carbon high-chromium die steel (hardened) and titanium alloy were used as workpiece materials for blind-and-through holes machining. Copper-tungsten was used as a tool electrode. The chemical composition and physico-mechanical properties are given in Table 1.

Table 1. Chemical composition and physico-mechanical properties of workpiece and electrode materials

Properties	Work piece material: Titanium alloy	Work piece material: Die steel	Electrode material
Specification	*Ti* 6*Al* 4V	T215 *Cr*-12	*Cu* W
Chemical composition (%)	*Al* - 6 V - 4	*C*-2.15, *Cr*-12 *Mn*-0.37, *Si*-0.22 *Mo*-0.8, *V*-0.8	*W*-80 *Cu*-20
Density (kg/m^3)	4500	7700	14700
Hardness	28 HRC	52-55 HRC	70 BHN
Thermal conductivity (W/M °K)	6.6	209	139
Electrical resistivity (μ Ω cm)	168	70	45
Melting temperature (°C)	1670	1536	3380
Boiling temperature (°C)	3285	2860	5555

Workpieces were machined in cube shape of size 25 × 25 × 10 mm, whereas the tool electrodes were machined in cylindrical shape of diameter 3 mm and length 70 mm. Die steel workpieces were hardened and tempered to HRC 52-55. Then, all the workpieces were ground finish. Commercial grade kerosene was used as dielectric. The dimensions of tool electrode and workpieces were chosen in accordance with the recommendations made by the College International Pour Letude Science Scientifique Des Techniques De Production Mechanique (CIRP)[2].

2.2 Equipment

The test specimens were spark-eroded on Fine Sodick Mark V NC EDM with servo-control and rotating heads with a provision to vary the speed of electrode. The specifications and test conditions are summarised in Table 2.

Table 2. EDM system specification and test conditions

Equipment	Fine Sodick Mark V CNC EDM
Open circuit voltage	90 V
Discharge current	3, 9, and 15 A
Pulse ON duration	20 and 200 μs
Electrode rotations	0, 500, 750 and 1000 rev/min
Servo-control	Electro-hydraulic
Dielectric	Commercial grade kerosene
Flushing system	Side flushing with pressure
Tool electrode polarity	Positive (+)
Type of machining	Through-and-blind hole

The workpieces were clamped in a precision machine-vice mounted on the machine table. The tool electrode was held in the drill chuck of rotating head. The speed of the rotating head could be varied by selecting the corresponding knob position. For through-hole machining, the work pieces were pre-drilled with diameter 2 mm holes and the electrode was passed through for extra length about 20 mm. In case of blind-holes, the depth was set to 3 mm in the beginning itself, irrespective of electrode frontal wear. The selected process parameters were fed into the computer programme. Stationary and rotating modes of electrodes were set by selecting the desired knob position.

2.3 Experimental Procedure

The test specimens were thoroughly washed in acetone and dried before weighing and machining. These samples were then mounted on the machine-vice provided with the electro-discharge machine and properly aligned. The machining parameters like pulse current, pulse duration, voltage and electrode rotation were set as per experimental plan (Table 3). The workpieces were allotted to different experimental combinations by using random number table[3].

Table 3. Fully randomised experimental plan

		Coded levels		
		-1	0	+1
		Electrode rotation (rev/min)		
Coded levels	Pulse current (A)	500	750	1000
-1	3	1 (9)	2(1)	3(3)
0	9	4 (5)	5(2)	6(4)
+1	15	7 (6)	8(7)	9(8)

Through-and-blind holes were made in the titanium alloy and die steel workpieces by setting the machining parameters through in-built computer. The holes were made by rotating and stationary electrodes. During rotary mode, the various speeds were used to assess the effect of rotating electrode.

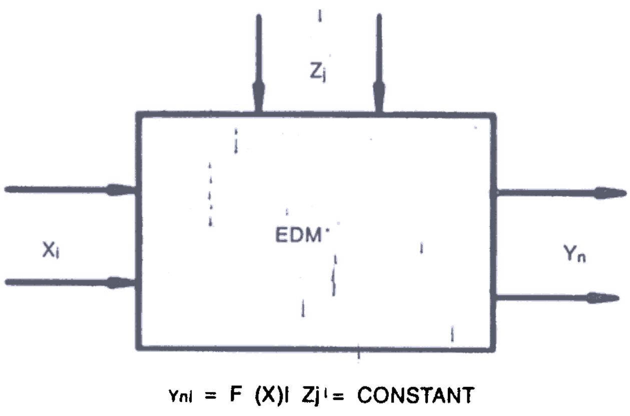

Figure 1. Cybernetic model of the EDM process

3. PROCESS MODELLING

A model for the EDM process was planned on the basis of cybernetic black box system. The present investigations into the effect of process parameters and physico-mechanical properties of work material on process responses are based on a model as shown in Fig. 1.

In Fig. 1, x_i (i = 1,2,...,K) are coded levels of K quantitative variables, whose effects on the process are to be investigated. For example,

- x_1 Pulse current
- x_2 Electrode rotation
- z_j (j = 1,2,....,m) are the factors held constant during the test, such as
- z_1 Pulse generator
- z_2 Open circuit voltage (90 V)
- z_3 Work material
- z_4 Dielectric fluid
- z_5 Tool electrode and its polarity
- z_6 Duty factor
- z_7 Hole depth for blind-hole machining (3mm), diameter of hole (3mm) and thickness of the workpiece (10 mm)
- z_8 Servo-control
- z_9 Diameter of electrode (3 mm), and
- Y_n (n = 1, 2,....u) are the measured values of the responses, such as
- Y_1 Metal removal rate
- Y_2 Electrode wear rate
- Y_3 Relative electrode wear
- Y_4 Surface roughness
- Y_5 Over cut
- Y_6 Out of roundness
- Y_7 Depth of heat-affected zone
- Y_8 Micro-hardness
- Y_9 Migration of material from either of the electrodes

The experimental work was planned in accordance with the model shown in Fig. 1 and the statistical techniques of experimental design.

3.1 Selection of Response Variables

The influence of rotating electrode as a flushing agent is reflected on several of the EDM process response variables as discussed above. The selected response variables and the instrumentation for their estimation are shown in Table 4.

Table 4. Response variables and the instruments used

Variable	Instrumentation for estimation
Machining characteristics	
Metal removal rate	Single pan balance with optical scale and in-built digital watch with an accuracy 0.01 s, outside micrometer and Interamass
Electrode wear rate	-do-
Surface roughness and surface roughness profiles	Surtronic-3 with *Ra* value in µm
Overcut	Outside micrometer and Intramass with 1 µm accuracy
Out of roundness	Taly Rond at magnification 500X.
Debris	
Size	Scanning electron microscope, ISI, UK with particle size marker. Magnification 250X and 2500X
Morphology	-do-
Chemical composition	Scanning electron microscope, ZEOL, Japan with energy dispersive spectroscope (EDS) and electron probe microanalyser (EPMA)
Surface integrity	
Texture	SEM
Chemical composition	SEM with EDS and EPMA
Heat affected zone (HAZ)	Metallurgical microscope and Vicker's micro-hardness tester
Micro-hardness	-do-
Photographs of holes and electrodes	Stereo-microscope at 10X and 'MONDA' optical digital micro-scope at magnification 10X and 20X

4. RESULTS & DISCUSSION

4.1 Design of Experiments

In many scientific investigations, it is required to study the effects of varying a number of factors on yield or quality of a product. In such situations, a conventional method of experimentation, i.e., varying one factor at a time and studying its effects, would be quite tedious and uneconomical, especially if the number of factors are large. Further, such experiments might not be able to predict the presence of interactions among different factors. The objective of the factorial experiment is to estimate the main effect and interactions among different factors which is not possible by other types of experiments. Interactions between two factors is defined as the change in the response when one of the factor's level is fixed and the levels of the other are varied. By proper designing, it is possible to estimate main as well as interaction effects with minimum number of experiments. One way of achieving this objective would be to decide upon a set of values or levels, for each of the factors to be studied, and to carry out one or more experiments with each of the possible combinations of the factor levels. Such an experiment is termed as full factorial experimental design and its results are valid for a wide range of conditions. Computational work is greatly simplified if the levels of the factors are so chosen that they fall at equal intervals on an ordinary or a transformed scale of preliminary experiment. These levels are decided on the basis of preliminary experiments, judgement, published literature and the limitations imposed by the experimental setup.

4.2 Polynomial Representation

If all the investigating factors are quantitative variables, then the true response or yield, Y, can be represented as a function of the level of these factors[4]

$$Y_{ni} = \varphi (x_i) \tag{1}$$

Where x_i (i = 1,2,.., K are coded levels of K quantitative variables. A knowledge of the response function φ, gives a complete summary of the results of the experiment and also predicts response for all values of x_i's that fall within the investigated region, but were not tested during the experiment. When the mathematical form of φ is not known, it can sometimes be approximated satisfactorily, within the experimental region, by a polynomial equation. The general form of a quadratic polynomial equation for the two factors x_1 and x_2 can be written as

$$Y_n = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 x_2 \quad (2)$$

The constants β_0, β_1 and β_2 are called regression coefficients and the polynomial of a regression function. The response surface given by Eqn (2) contains linear terms β_1 and β_2 in x_1 and x_2 respectively, square terms β_{11} and β_{22} in x_1^2 and x_2^2 respectively and the cross product terms β_{12} in $x_1.x_2$. The polynomial, like the one represented by Eqn. (2) could be fitted to the experimental points by the method of least squares. If $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ are least square estimates of β_0, β_1 and β_2, the fitted equation would be:

$$\hat{Y}_n = \hat{\beta}_0 + \hat{\beta}_1 x_1 + \hat{\beta}_2 x_2 + \hat{\beta}_{11} x_1^2 + \hat{\beta}_{22} x_2^2 + \hat{\beta}_{12} x_1 x_2 \quad (3)$$

where $\hat{Y}$ is the estimated response.

The estimation of the regression coefficients in Eqn (2) is the effect of each factor and must be studied atleast at three different levels. This suggests the use of a 3^2 factorial design. If the three levels of any factor x_i are coded as -1, 0, +1, the second order response surface equation is easy to derive[4,5]. Adequacy of the quadratic polynomial response equation must, however, be tested statistically to confirm the hypothesis of the quadratic polynomial response. The mathematical model thus obtained may be used for the optimisation of EDM process parameters.

4.3 Design of EDM Experiment

A 3^2 factorial design was chosen for all the experimental work presented in this paper. The design matrix for x-variables is shown in Table 5, where x_1 and x_2 were coded values of the variables whose effect on the response was studied, and yield Y' represented the measured value of the response, such as metal removal rate (MRR), electrode wear rate (EWR), relative electrode wear (REW) and surface roughness etc. The columns headed x_1 and x_2 which specified the actual combination of the factor levels used, constituted the plan for the experiment (Tables 3 and 5).

Table 5. Design matrix for a 3^2 factorial experiment

Trial no.	Factor level x_1^*	x_1^{**}	Yield y
1		-1	Y_1
2	-1	0	Y_2
3		1	Y_3
4	0		Y_4
5	0	0	Y_5
6	0	1	Y_6
7	1		Y_7
8	1	0	Y_8
9			Y_9

$^*x_1$ = -1 (3A) = 0 (9A) = +1(15A)

$^{**}x_2$ = -1 (500 rev/min) = 0 (750 rev/min) = +1 (1000 rev/min)

The total number of regression coefficients (N) possible are given by the expression[6]

$$N = \frac{n(n+3)}{2} + 1 \quad (4)$$

where, n = Number of factors.

The coded value of x can be related to the variable by the use of the following type of transformation equation:

$$x = \frac{2(\ln V - \ln V_{+1})}{\ln V_{+1} - \ln V_{-1}} + 1$$

where V is any variable (pulse current, electrode rotation etc.) V_{+1} and V_{-1} stand for +1 and -1 levels of the variable. In certain cases, linear transformation can also be made.

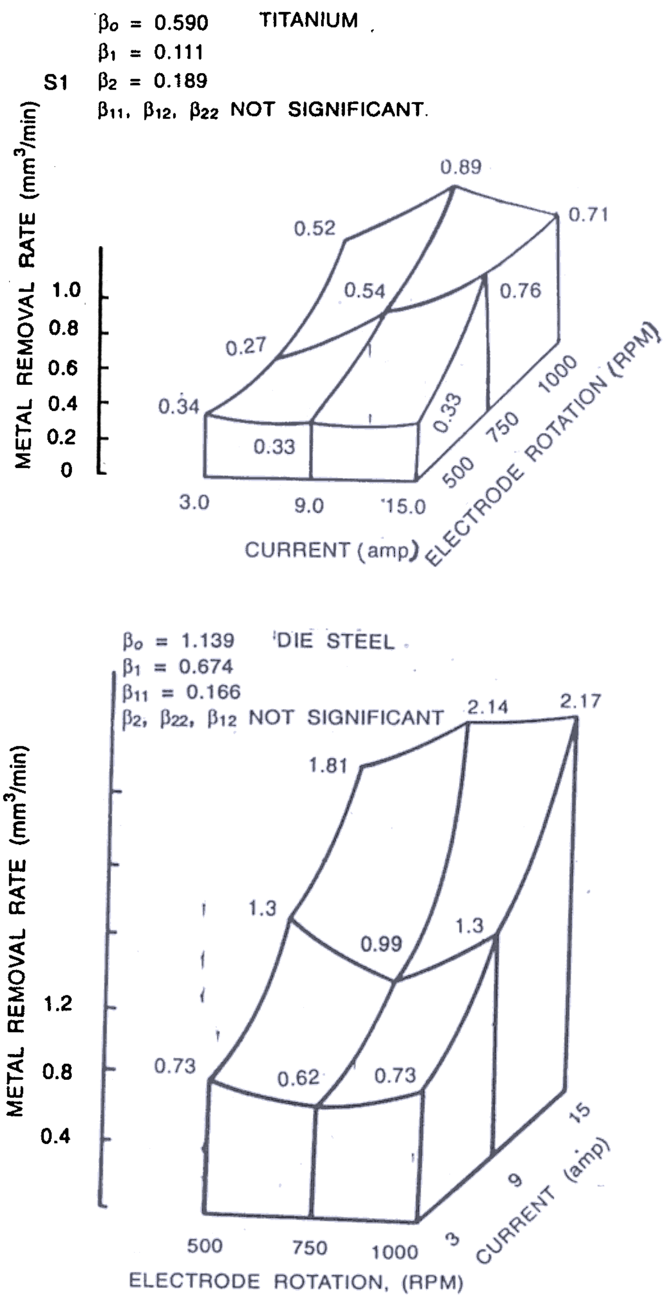

Figure 2. Response surfaces for metal removal rate

For two-factor factorial experiments, only six regression coefficients are possible. Accordingly, a second order polynomial would be adequate to represent the response surface. The adequacy of fit could be further checked by the coefficients of correlation. The response at different levels of a factor could also be represented geometrically. When only one factor was varied at a time, the response would be a curve. When two factors were varied simultaneously, the relationship would be represented by a surface called response surface. Figure 2 shows the response surfaces for MRR.

Details of the analysis and estimation of factorial effects and regression coefficients are given in Appendix A. The complete computer programme and flow chart are given in Appendices B and C.

5. CONCLUSIONS

1. A systematic and quantitative analysis of the observed data could lead to the equation governing the system performance which could be used to formulate its mathematical model.
2. With a properly designed experiment, it would be possible to determine the effect of changing any one variable. Its accuracy is same as if only one factor has been varied at a time and interaction effects between the factors.
3. Adequacy of the quadratic polynomial response equation must, however, be tested statistically to confirm the hypothesis of the quadratic polynomial response. The mathematical model thus obtained may be used for the optimisation of EDM process parameters.
4. The MRR was improved with rotating electrode due to improved flushing action and sparking efficiency (Fig. 2 and Appendix A).
5. MRR was higher in case of the die steel than titanium alloy (Fig. 2 and Appendix A).
6. The experimental response of combination of different treatments shows the optimum level of interactions at minimum and maximum values of factors. The purpose of fitting response surface is to estimate the response at certain points of interest.

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APPENDIX A

A 3^2 factorial experiment and response obtained (average from the two replications)

Pulse current level (A)	MRR (Die steel) (-1)	(0)	(+1)
	Electrode rotation level, rev/min		
	500	750	1000
3 (-1)	0.7308	0.6190	0.7330
9 (0)	1.3250	0.9895	1.2900
15 (+1)	1.8120	2.1406	2.1716

ANOVA for metal removal rate for die steel

Coefficient estimated	Estimate (β_{ij})	d.o.f	S.S.	M.S	Fcal
β_0	1.139		15.501	15.501	1926.122**
β_1	0.674		2.722	2.722	338.243**
β_2	0.054		0.018	0.018	2.212
β_{11}	0.166	1	0.055	0.055	6.875*
β_{22}	0.094	1	0.018	0.018	2.197
β_{12}	0.089	1	0.032	0.032	3.968
Due to regression		6	18.346	3.058	382.25 **
About regression		11	0.089	0.008	
Total		17	18.435	1.084	

*Significant ($P < 5\%$)
**Highly significant ($P < 1\%$)

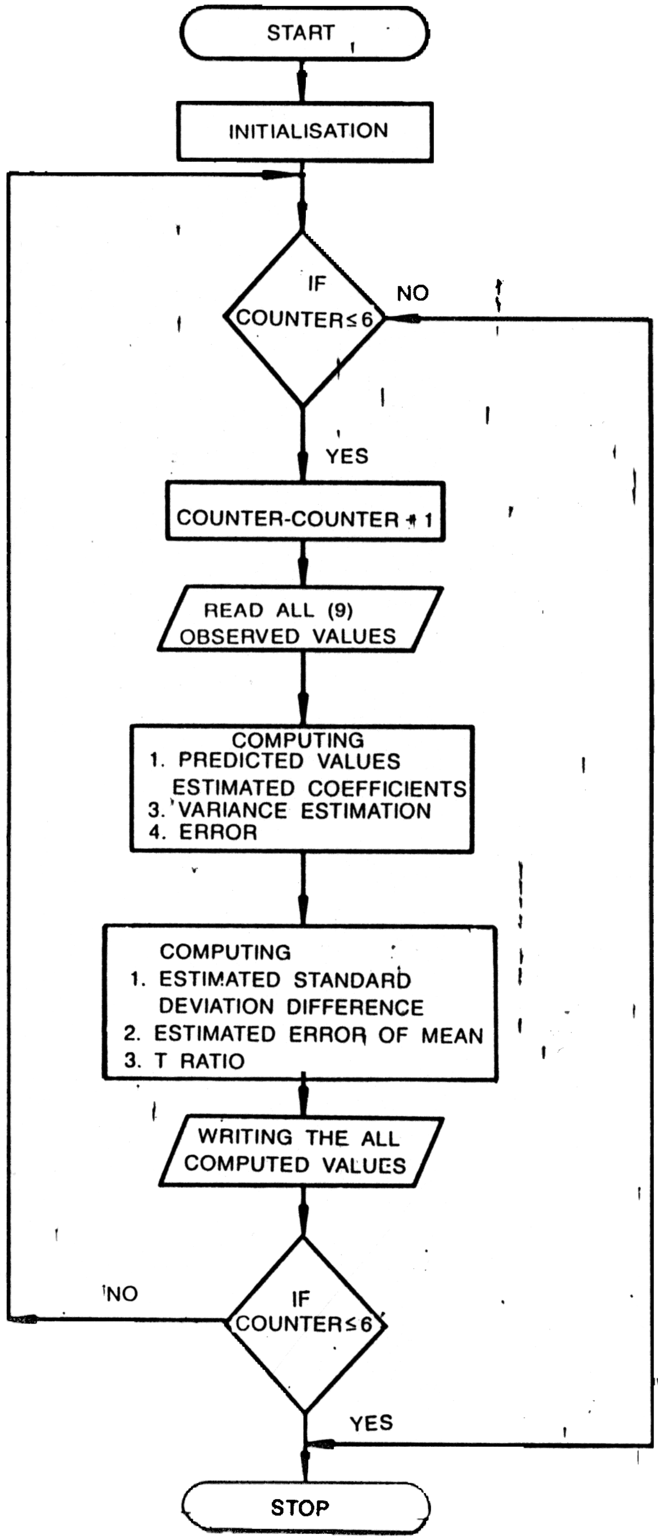
Hypothesis tested are: $H_0: \beta_{ij} = 0$
$F_{1,11}$ $(\alpha = 0.05) = 4.84$

Coefficient of correlation, $r = 1 - \frac{\text{SS about regr}}{\text{SS total}}$

$$= 1 - \frac{0.089}{18.435} = 0.9952$$

APPENDIX-B

.OW CHART OF COMPUTER PROGRAMME



APPENDIX-C

Computer programme for computing the values of coefficients of response surfaces

```
      INTEGER COUNTER
      DIMENSION YS(9), YT(9), X1(9), X2(9)
      OPEN (01, FILE = "SONI2.DAT",STATUS = "OLD")
      OPEN (09, FILE = "TSONI .RES".STATUS = "OLD")
      COUNTER = 1
80    IF (COUNTER. EQ.1) WRITE (9,71)
      IF (COUNTER. EQ.2) WRITE (9,72)
      IF (COUNTER. EQ.3) WRITE (9,73)
      IF (COUNTER. EQ.4) WRITE (9,74)
      IF (COUNTER. EQ.5) WRITE (9,75)
      IF (COUNTER. EQ.6) WRITE (9,76)
         SX2 = 0.0
         SX19 = 0.0
      READ (01,*) (YS(I) I = 1, 9), (YT(I) I = 1,9)
      N = 9
      DO 13 I = 1,9
      X1(I) = YS(I)-YT(I)
      SX19 = SX19+X1(I)
33    FORMAT (4F10.4)
13    CONTINUE
         XMEAN = SX19/N
         DO 14 J = 1, 9
         X2(J) = X1(J)-XMEAN
         SX2 = SX2+X2(J)*X2(J)
14    CONTINUE
         SDER = SQRT((SX2)/(N-1))
         SDERM = SDER/SORT(N)
         TR = XMEAN/SDERM
         WRITE (9, 44) SDER, SDERM, TR
44    FORMAT ('ESTIMATED STA. DEVIATION OF DIFFERENCE =',F10.5/,
      & 'ESTIMATED STA. ERROR OF MEAN =',F10.5/ ,'TRATIO =' ,F15.5)
C 71  FORMAT (10X , 'STEEL & TITANIUM (M R R)' /, 10X, 30 ('*'))
C 72  FORMAT (10X , 'STEEL TITANIUM (E W R)' /, 10X, 30 ('*'))
73    FORMAT (10X , 'STEEL & TITANIUM (R E W)' /, 10X, 30 ('*'))
74    FORMAT (10X , 'STEEL & TITANIUM ( OVER CUT)' /, 10X, 30 ('*'))
75    FORMAT (10X , 'STEEL & TITANIUM ( ROUNDNESS )' /, 10X, 30 ('*'))
76    FORMAT (10X , 'STEEL & TITANIUM ( SURFACE ROUGHNESS)' /, 10X, 35 ('*'))
71    FORMAT (10X , 'STEEL & TITANIUM (DEPTH OF RESOLIDIFIED LAYER)' /, & 10X, 55 ('*'))
72    FORMAT (10X , 'STEEL & TITANIUM (MICRO HARDNESS )' /, 10X, 35 ('*'))
         COUNTER = COUNTER+1
         IF (COUNTER. LE .6 .) GO TO 80
      STOP
      END
```