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Experimental Evaluation of Flow Formability of Sheet Metals for Armament Applications

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ABSTRACT

Flow forming is a promising process for the manufacture of certain critical armament components. This paper deals with the statistical design of an experiment carried out by the authors while flow forming different sheet metals employing various combinations of controlling variables in order to arrive at a functional relationship between flow formability (R_f) and controlling variables. The relationship established has been tested for its adequacy by proper analysis of variance (ANOVA). Response surface diagrams for a given R_f in the case of three specific materials are presented.

1. INTRODUCTION

The flow forming process has been playing an important role in the manufacture of many critical armament components. In addition, it has been finding application in aerospace and other general industrial sectors. Rocket motor tubes, warhead casings, cartridge cases, shape charge liners for antitank munitions, etc., which were hitherto manufactured by press-working, conventional spinning and other production processes, are now being produced by the flow forming process because of certain distinct advantages which make this process unique[1, 2].

Flow forming is a volumetric rotary forming process for obtaining the rotationally symmetric hollow metallic parts of various contours—conical, tubular, or curvilinear—to a high degree of accuracy and surface finish with improved mechanical properties. A schematic sketch showing the flow forming of a hollow sheet metal cone is depicted in Fig. 1. In this process, a flat sheet metal blank, locked against a rotating mandrel, revolves and the power-assisted forming rollers follow the mandrel contour, maintaining a preset gap. Under the application of considerable force through the powered rollers, the sheet metal blank is plastically deformed to the shape of the rotary mandrel, and the wall thickness of the contoured or conical finished part is heavily reduced. The relationship among the initial or starting blank thickness, T, the included cone angle, 2α, and the final wall thickness of the finished cone, t is represented by the sine law, $t = T \sin\alpha$. The percentage reduction in thickness, R can be calculated as:

$$R = \frac{T-t}{T} \times 100 = (1 - \sin\alpha) \times 100$$

Flow formability (R_f) may be defined as the relative ease with which a sheet metal can be shaped by the flow forming process and can be measured as the maximum percentage reduction in thickness a material can undergo just before fracture during flow forming[3]. Quantitatively,

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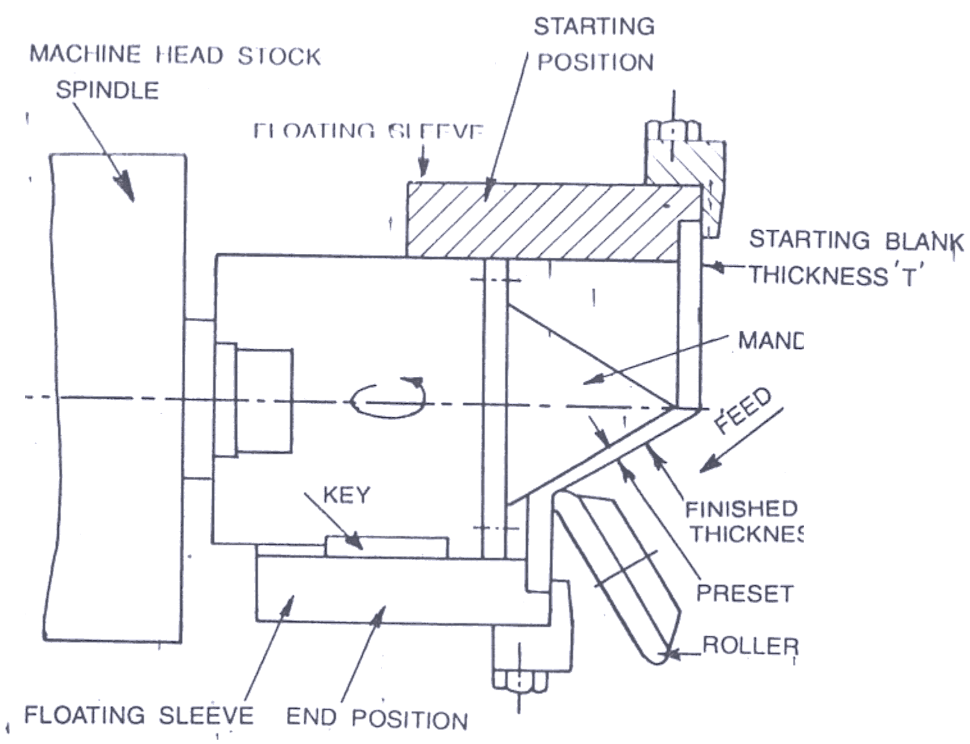

Figure 1. Schematic sketch showing flow forming of a hollow cone (upper half shows the starting position with metal blank before forming, while the lower half shows the end position after flow forming of the cone).

$$\text{Flow formability} = R_f = \frac{T - t_f}{T} \times 100 \qquad (1)$$

where

T is the original thickness of sheet metal and t_f is the final wall thickness of the flow-formed part just before fracture.

In the process of flow forming, as in the case of other metal forming processes, it is very much desirable to predict beforehand the R_f of the work-material; i.e. whether a given material would undergo a desired deformation before fracturing; otherwise there may be considerable waste in development work by trial-and-error method. Unfortunately, sufficient work has not been done in the area of evaluation of R_f, as is evidenced by lack of published literature on the subject.

The present paper deals with the statistical design and analysis of an experiment carried out by the authors while flow forming different sheet metals employing various combinations of process variables together with material variables in order to arrive at a functional relationship between R_f and the controlling factors (variables). The functional model postulated has been tested for its adequacy by proper statistical analysis of variance (ANOVA). Response surface diagrams for specific R_f and specific material are presented.

POSTULATION OF MATHEMATICAL MODEL

The statistical technique is used to increase the rate of convergence in the solution of problems. This is accompanied by an iterative procedure. The present work has become relatively simple, because the individual effects and interactions of the important controlling factors (variables) affecting the sheet metal R_f have been studied earlier by Roy and Bagchi[3]

The independent variables investigated were the sheet metal thickness, T (mm), the mandrel rotational speed, N (rpm), and the forming roller feed, f (mm/min). The response or the dependent variable was R_f. The functional relationship is now proposed as:

$$R_f = K\,T^{\alpha} N^{\beta} f^{\gamma}$$

This equation can be written in a more convenient form by taking logarithms of both sides

$$Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3$$

where

Y is the response of R_f on a logarithmic scale; X_1, X_2 and X_3 are the logarithmic transformations of T, N and f respectively, and B_0, B_1, B_2 and B_3 are the coefficients (constants). This equation can also be written as:

$$y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + e \qquad (2)$$

where

y is the observed value of R_f on a logarithmic scale; b_0, b_1, b_2 and b_3 are the estimates of the coefficients B_0, B_1, B_2 and B_3 respectively and e is the experimental error. Equation (2) is a polynomial of first degree. The coefficient of this linear equation can be estimated using the method of least square[4], which is explained later.

3. EXPERIMENTAL DESIGN

The experimental design used in this study is a composite design consisting of 12 trials which constitute a conventional 2^3 factorial design[5] with an additional centre point repeated four times. This arrangement of experimental points is shown in Fig. 2. The four coefficients in the R_f model postulated can be estimated from these trials. The repetition (replication) of the centre point provides an estimate of the experimental error from which the adequacy of the model can be checked.

3.1 Selection of Levels of Variables

The design of 12 trials provides three levels for each of the independent variables. Choice of the levels is made by considering the capacity of the flow-forming machine and the limiting flow-forming conditions. The levels of the variables used in the experiment are listed in Table 1.

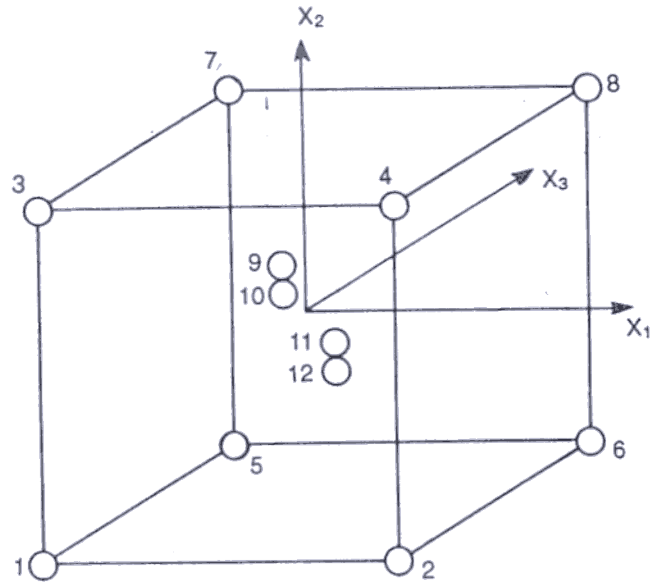

Figure 2. Arrangement of the experimental points indicating trial numbers in the experimental design.

Table 1. Levels of variables and their coding

Level	Metal thickness T (mm)	Mandrel rotational speed, N (rpm)	Forming roller feed, f (mm/min)	Coding X_1	X_2	X_3
Low	2	100	20	-1	-1	-1
Centre	3	600	70	0	0	0
High	5	1000	100	1	1	1

For convenience, the levels of the variables are coded so that the centre level corresponds to zero, the low level to -1 and the high level to 1 by the following transforming equations:

$$\left.\begin{aligned} X_1 &= \frac{\ln T - \ln 5}{\left(\dfrac{\ln 5 - \ln 2}{2}\right)} + 1 \\ X_2 &= \frac{\ln N - \ln 1000}{\left(\dfrac{\ln 1000 - \ln 100}{2}\right)} + \\ X_3 &= \frac{\ln f - \ln 100}{\left(\dfrac{\ln 100 - \ln 20}{2}\right)} + 1 \end{aligned}\right] \qquad (3)$$

The transformation equations are determined on the basis of flow-forming conditions. For example, the experimental unit for sheet metal thickness, T is (ln 5 – ln 2)/2. Thus, the metal thickness, T, can be transformed by first choosing appropriate scale and then dividing by its experimental design unit.

4 EXPERIMENTAL DETAILS

All tests and trials were conducted at the Armament Research & Development Establishment (ARDE), Pune, on a CNC flow-forming machine equipped with two hydraulically driven forming rollers and a 25 kW variable drive motor. The available process variables as well as material variables made the exact fitting of actual values of experimental design a little difficult. However, the effects of these discrepancies were found to be marginal.

4 Experimental Setup

Figure 3 shows the schematic sketch of the R_f test setup[3], which is similar to the one suggested by Kegg[6] and Kapakcioglu[7]. The test setup consists of a half ellipsoid mandrel of 200 mm minor diameter. The included cone angle of the ellipsoid at different sections varies from 180 deg. at the beginning of the flow-forming operation to 0 deg. at the end. Therefore, when a flatsheet metal blank is flow-formed over this mandrel, then according to the classical sine law ($t = T \sin\alpha$), the thickness of the flow-formed part will vary gradually from its original value to zero at the end. Consequently, sheet metals of all types and grades must fracture between these two limits.

Three different materials, namely, aluminium, copper and deep drawn grade steel (DDS); in sheet metal form, each with varying thickness (2, 3 and 5 mm) were tested for R_f under various combinations of process variables, as mentioned earlier. Original thickness of the sheet metals as well as their thickness at fracture were measured accurately, from which the maximum percentage reduction in thickness was calculated in each case using Eqn (1). The specifications of three different types of sheet metals on which the tests were conducted are given in Table 2.

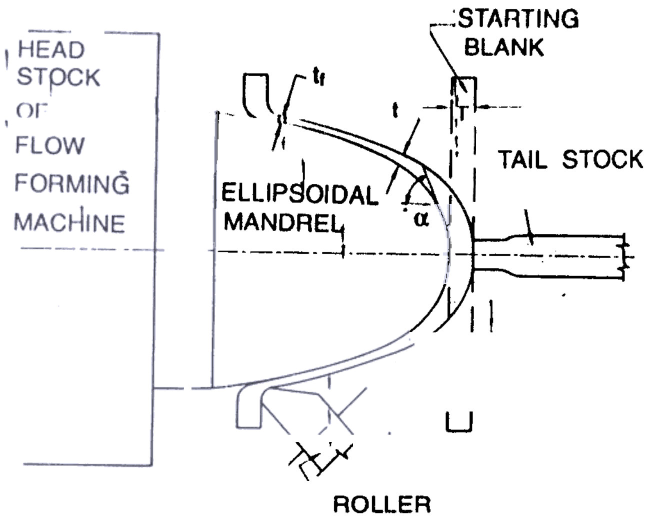

Figure 3. Scheme of experimental setup for R_f test

Table 2. Specifications of work materials

Specifications	Work materials (sheet metal)		
	Al	*Cu*	DD Grade Steel
Thickness (mm)	2, 3, 5	2, 3, 5	2, 3, 5
Hardness (VPN)	35 - 45	80 - 85	135 - 145
UTS (MPa)	145 - 155	240 - 250	430 - 440
0.2 % Proof Stress (MPa)	52 - 58	155 - 165	315 - 325
Elongation (%)	11 - 13	45 - 50	35 - 40
Reduction of Area (%)	78 - 82	65 - 70	68 - 72
Toughness (MPa)	12 17	101 105	153 155

Factors or independent variables which were used in the experiment are given in Table 1. They are material thickness, T (mm); rotational speed of mandrel, N (rpm); and feed rate of forming rollers, f (mm/min). Gap settings between the roller and the mandrel were maintained at the same values as calculated by the sine law. A suitable coolant was used in all the trials.

5. EXPERIMENTAL OBSERVATIONS & ANALYSIS

The responses, i.e. the R_f of the work material from 12 trials (under various combinations of different levels of the variables) were measured and

Table 3(a). Process variables and flow-formability results for three different sheet metals

Trial No.	Metal thickness, T (mm)	Mandrel rotational speed, N (rpm)	Forming roller feed, f (mm/min)	Flow formability, R_f(%) for *Al*	*Cu*	DDS
	2	100	20	78.50	81.25	
2	5	100	20	90.00	92.10	
3	2	1000	20	81.75	82.75	
4	5	1000	20	94.80	94.40	
5	2	100	100	76.75	68.00	
6	5	100	100	86.60	84.50	
7	2	1000	100	81.75	79.00	
8	5	1000	100	92.70	88.70	
9	3	600	70	86.20	83.50	
10	3	600	70	85.30	81.00	
11	3	600	70	87.00	85.50	
12	3	600	70	89.80	82.00	

Table 3(b). Coded variables and flow-formability results for three different sheet metals

Trial No	Coded variables X_1	X_2	X_3	Coded fow formability response, y(y = ln.R_f) *Al*	*Cu*	*DDS*
			-1	4.363	4.398	
2				4.500	4.523	
			-1	4.404	4.416	
4			-1	4.552	4.548	
5		-1		4.341	4.220	
6				4.461	4.437	
7				4.403	4.369	
		1		4.529	4.485	
9	0	0	0	4.457	4.425	
10	0	0	0	4.446	4.394	
	0	0	0	4.466	4.449	
12	0	0	0	4.498	4.407	

Al = Aluminium, *Cu* = Copper, DDS = Deep drawn Grade Steel

are recorded for each of three work materials in Table 3(a). The same table in coded form is shown in Table 3(b).

5.1 Evaluation of Flow Formability as a Function of Process Variables

From the 12 trials, the four coefficients (constants) in the postulated model, $y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + e$ could be estimated by the method of least square[4, 5]. The basic formula is

$$b = (X'X)^{-1}.X'y \tag{4}$$

where

b	Estimates of the coefficients
X	Design matrix of independent variabl
X'	Transposed matrix of X

$(X'X)^{-1}$ Inverse or reciprocal matrix of the product $(X'X)$

Matrix of the observed values of R_f

The design matrix of the independent variables X for the 12 trials is

$X =$	X_0	X_1	X_2	X_3	Trial No.
		-1			
	1		-1	-1	2
		-1			3
					4
					5
			-1		6
		-1			7
					8
		0	0	0	9
		0	0	0	10
		0	0	0	11
		0	0	0	12

Here, X_0 is a dummy variable whose value is unity in all the trials.

The transposed matrix X' is given by

$$X' = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ -1 & 1 & -1 & 1 & -1 & 1 & -1 & 0 & 0 & 0 & 0 \\ -1 & -1 & 1 & 1 & -1 & -1 & 1 & 0 & 0 & 0 & 0 \\ -1 & -1 & -1 & -1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Hence,

$$(X'.X) = \begin{bmatrix} 12 & 0 & 0 & 0 \\ 0 & 8 & 0 & 0 \\ 0 & 0 & 8 & 0 \\ 0 & 0 & 0 & 8 \end{bmatrix}$$

and

$$(X'.X)^{-1} = \begin{bmatrix} 0.0833 & 0 & 0 & 0 \\ 0 & 0.125 & 0 & 0 \\ 0 & 0 & 0.125 & 0 \\ 0 & 0 & 0 & 0.125 \end{bmatrix}$$

The matrix of y consists of a single column with 12 rows, e.g.

$$\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ \vdots \\ \vdots \\ y_{12} \end{bmatrix}$$

The values of $y_1, y_2, \ldots\ldots y_{12}$ are given in Table 3 (b) for three different work materials.

Therefore, Eqn (4) based on 12 trials can be written as

$$\begin{aligned} b_0 &= 0.0833\,(y_1 + y_2 + y_3 + \ldots\ldots + y_{12}) \\ b_1 &= 0.125\,(-y_1 + y_2 - y_3 + y_4 - y_5 + y_6 - y_7 + y_8) \\ b_2 &= 0.125\,(-y_1 - y_2 + y_3 + y_4 - y_5 - y_6 + y_7 + y_8) \\ b_3 &= 0.125\,(-y_1 - y_2 - y_3 - y_4 + y_5 + y_6 + y_7 + y_8) \end{aligned} \quad (5)$$

Equation (5) shows that calculation of the estimated coefficients (constants), b_0, b_1, b_2 and b_3 is a simple arithmetical operation. The values of the estimated coefficients are tabulated in Table 4.

Table 4. Values of estimated coefficients for the fitted model

Coefficient	Estimated values		
	Al	Cu	DDS
b_0	4.4517	4.4226	4.1023
b_1	0.0664	0.0737	0.1029
b_2	0.0279	0.0300	0.1309
b_3	-0.0106	-0.0468	-0.0146

The fitted model for evaluating R_f in terms of the input controlling variables is, therefore, as under:

a) For Al sheet metal

$$y = 4.4517 + 0.0664X_1 + 0.0279X_2 - 0.0106X_3$$

b) For Cu sheet metal

$$y = 4.4226 + 0.0737X_1 + 0.0300X_2 - 0.0468X_3$$

c) For DD steel sheet metal

$$y = 4.1023 + 0.1029X_1 + 0.1309X_2 - 0.0146X_3 \quad (6)$$

It should be noted that because of orthogonal property of the experimental design, the estimated coefficients, b_0, b_1, b_2 and b_3 are uncorrelated with one another. Further, because the method of least

Table 5(a). Analysis of variance format for the fitted model

Source of variation	Degree-of-freedom	Sum of square (S.S.)	Mean square (MS)	Calculated F ratio
Due to all fitted coefficients $(b_0, b_1, b_2, b_3, \ldots b_k)$	K	$\sum_1^N y^2 - \sum_1^N (y-\hat{y})^2$		
Due to zero order model (i.e. due to b_0 alone)	1	$\left(\frac{\sum_1^N y^2}{N}\right)$		
Due to first order model (i.e. due to $b_1, b_2, \ldots, b_k$)	k-1	$\sum_1^N y^2 - \sum_1^N (y-\hat{y})^2 - \left(\frac{\sum_1^N y^2}{N}\right)$	$\frac{\text{S.S}}{\text{d.f}}$	$\frac{\text{MS of the element}}{\text{MS of pure error}}$
Due to residual	N-k	$\sum_1^N (y-\hat{y})^2$		
Due to pure error	(n-1)	$\sum_1^n (yo-\bar{y}o)^2$		
Due to lack of fit	(n-k)- (n-1)	$\sum_1^N (y-\hat{y})^2 - \sum_1^n (yo-\bar{y}o)^2$		
Total	N	$\sum_1^N y^2$		

N No. of trials, k = No. of coefficients (constants)
n No. of repeated trials (replication)
y Observed values of results (response)
yo Observed values of repeated trials at centre point.
$\bar{y}o$ Mean of observed values of repeated trials at centre point
$\hat{y}$ Calculated values of results

square has been used, these estimates also possess the property of minimum variance.

5.2 Testing Adequacy of Postulated Model

Adequacy of the postulated model can be tested by making an analysis of variance (ANOVA) table. The ANOVA of the fitted R_f model for three different sheet metals (*Al, Cu* and DDS) is given in Table 5(b), while Table 5(a) shows the basic format and method of calculation for ANOVA. The ANOVA table provides essential information for the experiment which includes (a) sum of squares (SS); (b) degrees-of-freedom and (c) mean squares (MS). The mean square of 'lack of fit' can be compared with the mean square of pure error to test the adequacy of the postulated model, using the statistical F test.

From ANOVA Table 5(b), it is seen that the calculated F ratio of the mean square of lack of fit to the mean square of pure error is only 0.72, 2.1 and 8.06 for *Al*, *Cu* and DD steel sheet metals, respectively. But the standard tabulated F value with 5 and 3 degrees-of-freedom at 5 per cent significance level is 9, which is much higher than the calculated F values. Therefore, it can be concluded that the R_f models for all the three work materials, as postulated, are adequate. Further, the calculated F-ratios for the fitted coefficients and the first order effects are much higher than the tabulated 95 per cent F values with relevant degrees-of-freedom, which leads to the conclusion that all the coefficients or the first order effects are significant.

Table 5(b). Analysis of variance of fitted flow-formability model for different sheet metals

Source of variation		Degrees-of-freedom	Sum of square	Mean square	Calculated F ratio
Due to all fitted coefficients (b_0, b_1, b_2, b_3)	(for Al)	4	237.8503	59.4625	118925
	(for Cu)	4	234.7792	58.6948	97824
	(for DDS)	4	202.1602	50.5401	13300
Due to zero order model (i.e. due to b_0 alone)	(for Al)		237.8079		
	(for Cu)		234.7110		
	(for DDS)		201.9368		
Extra due to first order model (i.e. due to b_1, b_2, b_3)	(for Al)	3	0.0424	0.0141	28.20
	(for Cu)	3	0.0682	0.0227	37.80
	(for DDS)	3	0.2234	0.0744	19.59
Due to residual	(for Al)	8	0.0033	0.0004	
	(for Cu)	8	0.0080	0.0010	
	(for DDS)	8	0.1647	0.0206	
Due to 'pure error'	(for Al)	3	0.0015	0.0005	
	(for Cu)	3	0.0017	0.0006	
	(for DDS)	3	0.0114	0.0038	
Due to 'lack of fit'	(for Al)	5	0.0018	0.00036	0.72
	(for Cu)	5	0.0063	0.00126	2.10
	(for DDS)	5	0.1533	0.03066	8.068
Total	(for Al)	12	237.8536		
	(for Cu)	12	234.7872		
	(for DDS)	12	202.3249		

5.3 Generalized Flow Formability Equation

The fitted model postulated in Eqn (6) for Al, Cu and DD steel sheet metals can now be transformed into a generalised form by the equation (3) as

a) For Al sheet metal

$$R_f = 66.4\ T^{0.145}\ N^{0.024}\ f^{0.013}$$

b) For Cu sheet metal

$$R_f = 74.3\ T^{0.161}\ N^{0.026}\ f^{0.058} \tag{7}$$

c) For DD steel sheet metal

$$R_f = 26.0\ T^{0.225}\ N^{0.114}\ f^{0.018}$$

5.4 Response Surface for Flow Formability

The relationship between the levels of controlling factors (independent variables) and the corresponding responses, as given by Eqn (7), can be depicted geometrically on a 3-D model, called response surface[5]. As examples, the response surface diagrams for a specific R_f are illustrated in Fig. 4, Fig. 5 and Fig. 6 for Al, Cu and DD steel sheet metals, respectively. It can be easily understood that numerous choices of controlling factors (forming conditions) can be made for a given constant R_f. On the other hand, R_f can be quantitatively evaluated for a given set of controlling factors (variables). The response surface model (diagram) can be utilised for optimisation purposes.

5.5 Correlating Mechanical Properties of Work Materials

The R_f model was evolved correlating the metal thickness and other process variables; and three equations were derived for the three materials

$$R_f' = 66.4\ T^{0.145}\ N^{0.024}\ f^{-0.013}$$

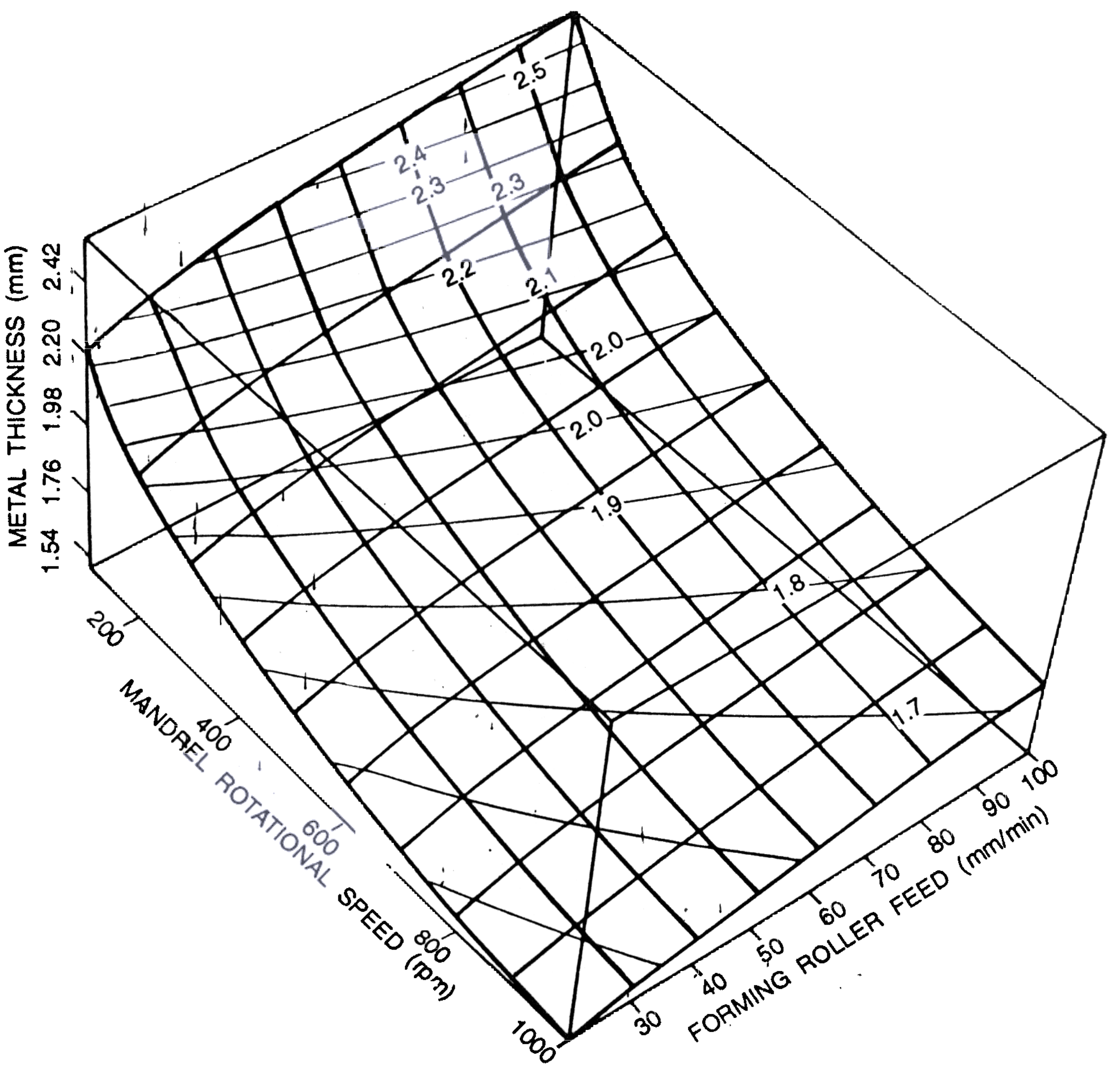

Figure 4. Response surface diagram for R_f of Al sheet metal (for $R_f = 80$ %)

under investigation. Mechanical properties of the materials were not included in these equations. For the purpose of visualising the individual effects of material properties, the values of R_f were compared with various mechanical properties like 0.2 percentage proof stress, percentage elongation, percentage reduction of area and toughness for each work material tested at a particular combination of controlling variables. It was observed that the most consistent and logical correlation could exist with the material toughness which is a combined property of material strength and ductility. The relationships between R_f and various mechanical properties of material are graphically presented in Fig. 7.

6. CONCLUSIONS

(a) Testing and evaluation of R_f can be more economically and effectively done by proper statistical design and analysis of experiment than by the conventional one variable-at-a-time methods. For example, 12 trials are good enough to fit a first order R_f equation with the three variables under investigation in the present work.

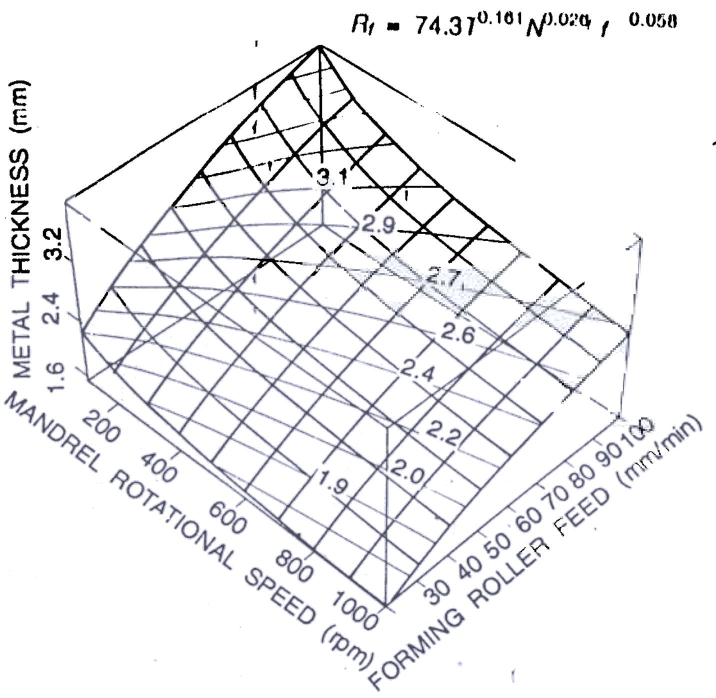

Figure 5. Response surface diagram for R_f of *Cu* sheet metal (for R_f = 80 %).

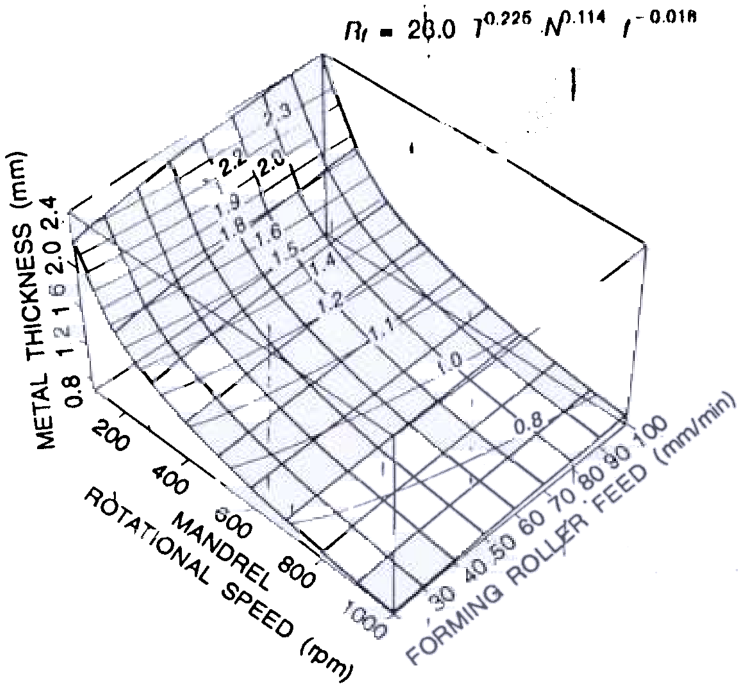

Figure 6. Response surface diagram for R_f of DD steel sheet metal (for R_f = 60 %).

(b) Within the region of the experiment, R_f of three different materials can be predicted by simple first order equations.

(c) The four coefficients (or exponents/constants) in the postulated (predicting) equations are independently determined.

(d) The adequacy of the fitted model and significance of the constants/coefficients have been tested statistically.

(e) As can be seen, the R_f of a sheet metal is related not only to the material properties (specification), but also to the material thickness and other process variables like rotational speed of the mandrel and feed rate of the forming rollers. The functional relationship of R_f with the process variables (as evaluated in this paper) is very much desirable to predict beforehand whether a material of given properties would undergo a desired reduction before fracturing. Further, for constant R_f, numerous choices of forming conditions can be made. On the other hand, R_f can be evaluated for a given forming condition in the case of the

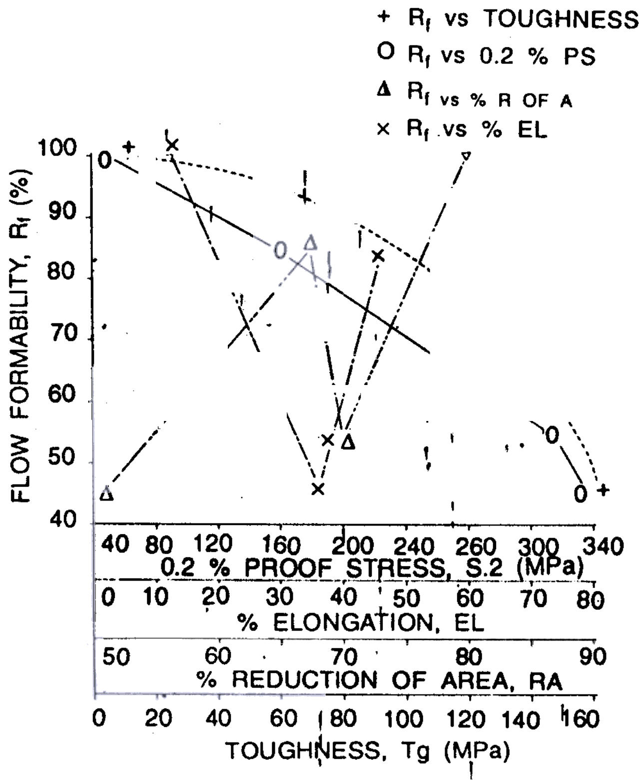

Figure 7. Relationship between R_f and mechanical properties of materials.

three specific sheet metal materials under investigation.

(f) Three separate equations for evaluating R_f of three specific materials have been established. However, there is further scope for including the material properties as a fourth variable in the predicting equation, so that a broad universal equation can be established, which will be applicable to all materials.

It is hoped that the findings of this study will be useful to practising engineers for design and manufacture of the critical armament components with stringent specifications which are to be manufactured by flow-forming technique.

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