Chapter - 6

CONCLUSIONS

"Everything should be made as simple as possible, but not simpler".

.... Albert Einstein

CONCLUSIONS

With the development of industrial research, the methodology of research itself has undergone vast changes, the emphasis being brevity within reasonable limit of accuracy. The method must be systematic and concise - but conducive to precision and accuracy.

Testing and evaluation of the flow formability of materials as well as the dimensional accuracy and surface finish of flow formed cones of different materials can be much more economically and effectively done by proper statistical design and analysis of experiment than by conventional one variable-at-a-time method.

The methods used for the objective and purpose of the present project are :

(a) Factorial design of experiment and Analysis of Variance for assessing the degree of significance of the controlling factors affecting the objective parameters or end results.

(b) Response surface methodology for evolving the response functions (predicting equations) relating the objective parameters (dependent variables) with the controlling factors (independent variables).

(c) Direct search technique for optimisation of the response functions (objective equations) in order to obtain the optimum values of the controlling factors at which the objective parameters attain the minimal values.

These methods and viewpoints have already been proved very useful in other engineering research work, particularly in the field of agricultural and chemical engineering as well as to some extent in the field of metal-cutting; but has not yet been used in the area of flow forming research.

6.1 SUMMARY OF THE MAJOR FINDINGS/EXPERIMENTAL RESULTS

6.1.1 For the work on flow formability of materials, the experimental design used was a composite design consisting of 12 trials which constituted a conventional 2^3 factorial design with an additional center point repeated four times. Based on the experimental observations (responses), three separate response equations [Eqn (3.12) or Eqn. (3.14)] for evaluating the flow formability of three specific materials (in sheetmetal form) have been established and tested for their adequacy which are as under :

(i) $R_f = 66.4T^{.145} \; N^{.204} \; f^{-.013}$ for Aluminium

(ii) $R_f = 74.3T^{.161} \; N^{.026} \; f^{-.058}$ for Copper

(iii) $R_f = 26.0T^{.225} \; N^{.114} \; f^{-.018}$ for DD Steel

where R_f is the flow formability measured in terms of maximum percentage reduction in cone-wall thickness at fracture; and T, N & f are the original thickness of the material, the mandrel rotational speed and the forming roller feed having the experimental range of 2 - 5 mm, 100 - 1000 rpm and 20 - 100 mm/min respectively.

In addition, the second order non-linear equations including interaction effects have also been evolved vide Eqn. (3.16). However, the two-factor or three-factor interaction effects were found to be statistically not significant.

3-Dimensional response surfaces for flow formability based on the above equations have been illustrated in Fig. 3.11 to Fig. 3.13, which will help in choosing suitable combination of factor levels for a given flow formability of any of the three specific materials.

6.1.2 For the assessment and evaluation of dimensional accuracy and surface finish of flow formed cones, a 3^3 factorial design, consisting of 27 trials with each trial replicated twice, was employed. Two sets of response equations have been evolved for predicting the dimensional accuracy and the surface finish of flow formed cones made from aluminium and copper sheetmetals vide Eqn. (4.9) to Eqn. (4.12). These are as under :

i)

$$\hat{y}_{aa} = 4.1800 + 1.5394 X_1 - 1.2844 X_2 + 1.7672 X_3 - 0.3083 X_1^2 + 0.2300 X_2^2 + 0.1783 X_3^2 - 0.3583 X_1X_2 + 0.3258 X_1X_3 + 0.1317 X_2X_3 + 0.2437 X_1X_2X_3$$

ii)

$$\hat{y}_{ca} = 5.6874 + 2.6628 X_1 - 1.5578 X_2 + 1.5356 X_3 - 0.4539 X_1^2 + 0.2311 X_2^2 + 0.0911 X_3^2 - 0.3617 X_1X_2 + 0.0317 X_1X_3 + 0.0675 X_2X_3 + 0.1325 X_1X_2X_3$$

iii)

$$\hat{y}_{as} = 1.9536 - 0.2367 X_1 - 0.4333 X_2 + 0.3536 X_3 + 0.0178 X_1^2 + 0.1794 X_2^2 + 0.0119 X_3^2 + 0.0104 X_1X_2 - 0.0200 X_1X_3 - 0.0262 X_2X_3 + 0.0700 X_1X_2X_3$$

iv)

$$\hat{y}_{cs} = 1.7580 - 0.2731 X_1 - 0.3381 X_2 + 0.3081 X_3 - 0.0619 X_1^2 + 0.1164 X_2^2 - 0.0819 X_3^2 + 0.0337 X_1X_2 - 0.0629 X_1X_3 - 0.0700 X_2X_3 + 0.0556 X_1X_2X_3$$

Where y_{aa} & y_{ca} are the dimensional accuracy in terms of the upper deviation of cone-wall thickness $(\delta t)_u$ in percentage of the set gap of sine thickness for aluminium and copper flow formed cones respectively; y_{as} & y_{cs} are the surface finish in terms of mean roughness value of center line average Ra in μm on external surface of aluminium and copper cones respectively; X_1, X_2 & X_3 are the transformed independent variables derived from the controlling factors like percentage reduction in cone-wall thickness R (%), mandrel rotational speed N (rpm) and the forming roller feed f (mm/min), the transformation relation being $X_1 = (R - 50) / 14$, $X_2 = (N - 550) / 350$ and $X_3 = (f - 60) / 40$. The experimental range of the controlling factors R, N & f is 36 - 64%, 200 - 900 rpm and 20 - 100 mm/min respectively; or in the experimental design unit, each of the independent variables X_1, X_2, X_3 ranges from -1 to +1.

The response surface contours in 3-Dimensional graphical form have been drawn for dimensional accuracy and surface finish of flow formed cones made from two specific materials (Al & Cu) vide Fig. 4.12 to Fig. 4.15.

6.1.3 Optimisation of the objective functions for dimensional accuracy and surface finish of flow formed cones has been carried out under two categories, namely, unconstrained and fully constrained optimisation for which suitable computer programs have been created using MATLAB software.

Within the range of the experiment, unconstrained optimisation of dimensional accuracy functions for flow formed cones without any constraint on the limit of surface finish R_a gave the optimal values of the controlling factors as follows: R_{opt} = 36% [or $(2\alpha)_{opt}$ = 80^0], N_{opt} = 900 rpm and f_{opt} = 20 mm/min at which the percentage upper deviation of cone-wall thickness $(\delta t)_u$ attained a minimum value of 0.4851% and 0.2579% for aluminium and copper flow formed cone respectively.

In the similar way, the unconstrained optimisation of surface finish equations for flow formed cones yielded the optimal values of the controlling factors as R_{opt} = 64% [or $(2\alpha)_{opt}$ = 42^0], N_{opt} = 900 rpm, f_{opt} = 20 mm/min at which surface roughness R_a attained a minimum value of 1.1257 μm and 0.9223 μm respectively for aluminium and copper flow formed cones.

Full constrained optimisation of dimensional accuracy functions with finite variable bounds and subject to a surface finish upper limit of 1.7 μm (R_a < 1.7 μm) produced the following output: R_{opt} = 36% [or $(2\alpha)_{opt}$ = 80^0], N_{opt} = 900 rpm, f_{opt} = 20 mm/min at which the optimal accuracy $[(\delta t)_u]_{opt}$ = $[(\delta t)_u]_{min}$ = 0.4851% and 0.2579% and the corresponding surface roughness R_a = 1.6783 μm and 1.3865 μm respectively for aluminium and copper flow formed cones.

Results of all types of optimisation study have been represented by 2-D and 3-D plots in Fig. 5.1 to Fig. 5.14.

6.2 IMPORTANT INFERENCES

Based on the summary of experimental results and the major findings, the following important inferences can be made :

1. Only 12 trials of a properly designed experiment are good enough to fit a first order linear model as well as a second order non-linear model of flow formability equations relating three controlling factors (independent variables) under investigation.

2. Within the experimental range of the controlling factors, the flow formability of three different materials (aluminium, copper and DD grade steel sheetmetals) can be predicted with adequate precision by the simple first order linear equations [Eqn. (3.12) & Eqn. (3.14)].

3. The flow formability of a material (sheetmetal) is influenced not only by the material properties but also by the material thickness T and other process variables like mandrel rotational speed N and forming rollers feed f which differs from the findings of earlier researchers.

4. From the graphical plot of individual effects of various mechanical properties of material like 0.2 proof stress, % elongation, % reduction in area and toughness against the flow formability of different materials, it is observed that the most

consistent and logical correlation can exist with material toughness which is a combined property of material strength and ductility.

5. Response surface diagrams for flow formability [Fig. 3.11 to Fig. 3.13] show that for a given flow formability, numerous choices of forming – conditions (factors combinations) can be made. On the other hand, the flow formability can be evaluated for a given forming condition in the cases of three specific materials under investigation, namely, aluminium, copper and DD steel sheetmetals.

6. A 3^3 factorial design of experiment consisting of 27 trials with two replicates of each trial is found to be sufficient for assessment and evaluation of dimensional accuracy and surface finish of flow formed cones.

7. Analysis of 3^3 factorial experiment shows that not only the linear effects but also the quadratic effects of the controlling factors like percentage reduction in thickness R, mandrel rotational speed N and forming rollers feed f as well as some of their interactions have significant influence on the dimensional accuracy and surface finish of the flow formed cones made from aluminium and copper sheetmetals.

8. Second degree equations (with an additional third degree term), viz. Eqn. (4.9) to Eqn. (4.12), evolved from the experimental data and tested statistically for their goodness of fit, are adequate to predict the dimensional accuracy and surface finish of aluminium and copper flow formed cones.

9. Response surface contours for dimensional accuracy and surface finish of flow formed cones (Fig. 4.12 & Fig. 4.13) illustrate that for obtaining a constant upper deviation of cone-wall thickness $(\delta t)_u$ or constant surface finish Ra on external surface of the cones, choice can be made from numerous combinations of various levels of the controlling factors R, N and f. On the other hand, $(\delta t)_u$ and Ra of the

flow formed cones can be quantitatively evaluated from a given combination of controlling variable levels.

10. From optimisation study of the objective functions for dimensional accuracy and surface finish of the flow formed cones, it is seen that global or totally unconstrained optimisation without any variable bound, the optimum combination of the levels of controlling factors (independent variables) lies outside the meaningful range of the experiment for all cases, whether for aluminium or copper cones. No critical point (maxima or minima) lies within the domain bounded by the experimental range of the variables X_1, X_2 and X_3 which are the transformed variables of the controlling factors R, N & f in experimental design units. In fact, the optimal values lie on the corners of the six surfaces defined by $X_i = -1$ and $X_i = +1$ where i = 1, 2, 3.

11. From the output of the programs for optimisation of accuracy and surface finish functions, it is revealed that within the region of the experiment, both unconstrained and constrained optimisation of the accuracy functions give the same result provided constraint on the upper limit of surface roughness is 1.7 μm or more; because the surface roughness, Ra corresponding to minimum $(\delta t)_u$ never exceeds 1.7μm.

12. The optimal values of N and f at which $(\delta t)_u$ is minimal subject to the constraint Ra < 1.7μm is same for all R or 2α, viz. N_{opt} = 900 rpm, f_{opt} = 20mm/min.

Concluding Remarks :

The project work on the assessment, evaluation and optimisation of processing parameters in flow forming of sheetmetal cones of different materials, as carried out, studied and embodied in the present thesis, will certainly help the Mechanical and Production Engineers to better understand the flow forming process, effectively control the process variables for improving performance characteristics and finally obtain the flow formed parts with higher accuracy, smoother surface finish, ease of production and increased reliability operating within the envelope of reasonable economics.

6.3 SCOPE FOR FUTURE WORK

There is vast scope for further work in the field of flow forming in manifold directions, a few being outlined below :

(i) Separate equations for evaluating the flow formability of three materials and the accuracy and surface finish of flow formed cones made from two materials have been established. However, there is a further scope for experimenting with other important materials so that the material properties can be included as fourth independent variable in the predicting equations, thus establishing a set of broad universal equations which will be applicable for all materials.

(ii) Effects of geometric elements of the forming rollers as well as their setting angles may be investigated with a view to develop some functional relationship between them and the performance characteristics like flow formability, accuracy and surface finish. However, this type of experiment is likely to be very costly and time consuming.

(iii) Influence of all these input process variables (controlling parameters) can be studied to evaluate their quantitative effects on the flow forming force components (power consumption) as well as improvement in mechanical properties of flow formed parts.