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STUDY OF THE INFLUENCES OF PROCESS PARAMETERS ON COLD FLOW FORMING OF AL-TUBES

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Abstract: Manufacturing of thin-walled precision shells of non-ferrous materials is made using an inclusive manufacturing approach through cold flow forming process. To understand the influence of the input parameters on this complicated process is the prime aim of this study. There exists no guideline to set the inputs for a set of desired output. Usually, trial and error approach is followed by the operator. Therefore, an analytics procedure is followed to set the process parameters based on inclusive manufacturing approach. A total of 136 shells are fabricated varying three different inputs, and three responses that lead to defects are measured. Finally, the influence of inputs on outputs is analyzed using regression technique. It has helped to set the manufacturing tolerance beforehand and could reduce the defects.

Key words: flow-forming, thin-walled precision Al-tubes, manufacturing analytics, design of experiments.

1. INTRODUCTION

Inclusive manufacturing is the modern day demand, and a large number of researchers are working on the same. The primary aim is to empower the quality in manufacturing products through the inclusion of a large heterogeneous population base and varieties of manufacturing technologies. It helps to develop eco-friendly products and services using IoT, virtual reality, and computerised numerical control techniques. It also ensures the cross-training of the human employees of a company and empowerment of their life cycles. Therefore, for the development of sustainable products and to accommodate the rapidly changing manufacturing products, different small and large size companies and a broad spectrum of domain experts has to come together and work as a combined unit. It will fulfill customized needs of the end user. The challenge is enormous, and lots of research is left [1].

Flow forming is a semi-automated process and is finding broad applications in defence and aerospace sectors. Rocket motor shells, gas turbine parts, airframe hardware, dish antennas, power train components, wheel rims of automobiles, gas bottles and cylindrical containers are manufactured using flow forming process. It is also used by radioactive material packaging community to fabricate small containment vessels. A variety of products are to be manufactured from the same machine with the help of similar kind of human resources. The accuracy of those products largely depends on the operator. On the other hand, peoples are demanding for the thin section and lightweight parts, manufacturing of which is extremely difficult using spinning/flow forming process alone. Inclusive manufacturing approach has to be applied to facilitate this need.

The thickness of the flow formed product is determined by suitably setting the gap between the mandrel and the rollers. The final shape of the finished product is obtained through multiple runs. Plastic deformation occurs in the specimen. Surface roughness, micro-cracks, diametral growth, out-of-roundness and premature bursting are some of the defects commonly observed in the flow forming process [1]. Also, this involves large-scale, expensive machine tools. To get a quality product, flow former should specify the shape, material properties and the amount of the material beforehand. Therefore, there is a vast scope for manufacturing automation of the process and requires intelligent decision support model to control the input parameters. While doing so, quality, the involvement of human being, energy consumption, repeatability and sustainability of the finished products is getting improved. We have to make a trade-off between the automation and high quality, near net-shaped manufacturing products with sophisticated machines and highly trained operator. Here, the basic idea is to promote an inclusive approach in designing the process for manufacturing tubes using flow forming process. Researchers are working on these issues. Quite a few techniques (statistical, soft computing-based) are available in the literature.

DOE along with RSM was applied by Majagi et al. [2] to generate the relationship between three inputs, namely, feed rate, speed and coolant properties with four outputs flow formed Al-sheets. It has shown excellent accuracy compared to the experimental results. Momani et al. [3] built DOE and FE-based predictive models for a metal blanking process. Air bending of electro-galvanized steel sheets was modelled using RSM by Vasudevan and Srinivasan [4]. Spring-back is one of the principal problems associated with a metal forming process. Material and dimensional properties of the workpiece material, applied force, lubrication and other forming process parameters play an essential role in this regard. Chen and Koc [5] used DOE and FEA for this purpose. Hu et al. [6] used RSM in combination with PSO for the similar purpose. Narayanasamy and Padmanabhan [7] used regression and neural networks for the same. They considered five inputs and spring-back of the sheet as the output parameter and utilized regression and NN tools for modelling the process. The NN-based model was found to be more accurate compared to the regression model. Torabi et al. [8] used RSM and NSGA-II for optimal production of turbine blades. They maximized the filling ratio of the last die and minimized the volume of flash, resultant force during forging and strain variance of the last blade. Xiong et al. [9] also developed NN and regression-based predictive models for a robotic welding process. They have observed that prediction accuracy of the NN-based model is better in comparison to regression technique. Cicek et al. [10] employed Taguchi method and RSM in the optimization of drilling parameters. Radhakrishnan and Nandan [11] derived an empirical equation for end milling operation having three inputs and one output. They have eliminated abnormal experimental data with the help of regression model and have used the final set of filtered data for development of neural network model. Fuzzy logic and regression analysis have been used by Kovac et al. [12] for modelling a face milling operation with three inputs and one output. Fuzzy logic-based model is seen to be more accurate compared to the regression analysis. Kuram and Ozcelik [13] used Taguchi method for modelling a micro-milling process applied on a very tough material. They considered a multi-inputs, multi-outputs model development using regression analysis and fuzzy logic. The effectiveness of both the models was found to be comparable when used to predict the output parameters. Effects of input parameters in resistance spot welding (RSW) have been analysed by Muhammad et al. [14]. Further, they have used response surface methodology for the establishment of an empirical relation for prediction of weld zone development. Therefore, regression analysis could be a tool for analysing the effects of process parameters on different manufacturing processes.

Some investigators also do experimental as well as simulation studies of flow forming process. Rajan et al. [15] studied the effect of heat treatment on the mechanical properties of flow formed shells. The same authors [16] also examined the suitability of various burst pressure prediction formulas and their modifications on flow-formed thin-walled high strength shells. Defects generated in flow forming of steel tubes have been experimentally investigated by Rajan and Narasimhan [17]. Although there exists numerous such methods in the literature but development of multi-variable input-output relationship on experimental studies of flow forming of aerospace materials are limited in numbers [18]. It is only because of the limited availability of full-scale flow forming machine and associated process expertise. In the present study, inclusive manufacturing approach is applied for the production of thin Al-tubes used by defence sectors. After that, a manufacturing analytics is carried out using regression analysis to find the impact of the process parameters on different outputs.

2. PROBLEM FORMULATION

Flow forming is exceptionally suitable for the production of a high precision thin-walled tube. This process has several advantages compared to the conventional metal spinning process [19]. In this process, the thickness of hollow cylinders/shells is reduced with the help of mandrel and a set of rollers. Deformation occurs at the plastic stage [20, 21] and up to 90% of the thickness is reduced. The inside surface quality of the finished work-piece is almost same with the outside surface quality of the mandrel. Due to the inherent advantages associated with the process, it has found larger acceptability in defense, aerospace and automobile industries [22].

However, quality of the finished products demands the proper selection of inputs. Further, there is no established guideline for the selection of process parameters. Hence, we need highly skilled operator [23-24] to run the machine. Most of the time, parameters are set through several numbers of initial trials. In this process, a considerable amount of time is lost, leading to loss of productivity and non-optimum utilization of resources. Thus, the establishment of flow forming process parameter for any new product is not only time consuming but also a cost-intensive procedure. Also, the process involves large-scale, expensive machinery and associated tooling. Therefore, there is a need for a decision-making tool for automating such a complicated process. The primary motivation of this study lies in this. In this study, the authors tried to improve the shape accuracy of the finished products using production automation techniques. Shape accuracy (i.e., diameter opening and out-of-roundness) is seen to be dependent on three significant parameters namely axial stagger, feed to speed ratio and infeed of ther roller. H30 Aluminum alloy tubes are fabricated, and relevant data are extracted for further analysis of the process.

Proposed inclusive manufacturing approach applied in this study is explained with the help of Figure 1. Such model enables the designer to consider the manufacturing process capability in the selection of their design tolerance. The predictive ability of the developed model is used to identify the possible tolerance levels which can further be used by a designer to update his design requirements. Such inclusive approach ensures identification of possible tolerance levels beforehand the actual production trails, leading to more realisable design where manufacturing aspects are also embedded. Therefore, the proposed predictive model can also be considered as a tool towards DFM.

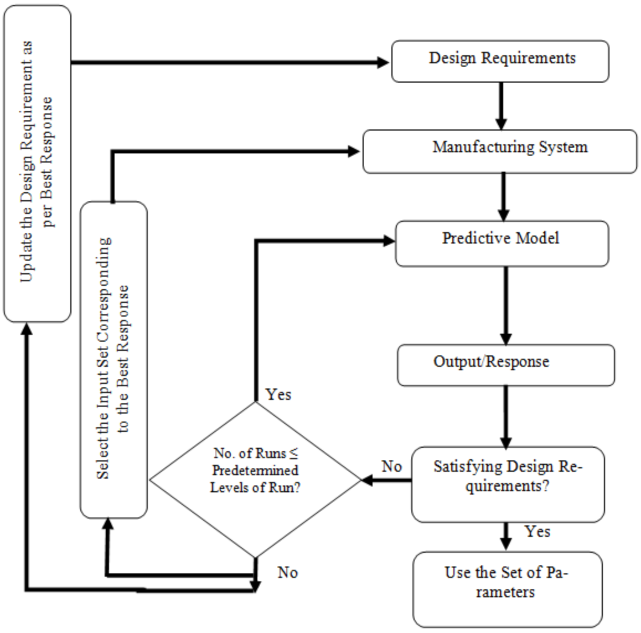


Fig. 1. Flowchart for improving design feature using the predictive model

2.1. Fabrication of H30 Aluminum alloy tubes

The present flow forming experimentation has been carried out in solution annealed H30 Aluminum alloy on a 3-rollers, 4-axes CNC machine (refer to Figure 2). The maximum forming diameter is 560mm, and maximum length of the flow formed product is 1800mm. Rollers can apply a radial force of180kN, and an axial force of 300kN.

The raw material, more commonly known as ‘Preform’, is a shell of 118mm and 132mm as internal and external diameters, respectively. The initial length of the preform is 180mm. The tools required for flow forming are a mandrel, stripper ring, toothed ring (usually known as drive ring) and forming rollers. The outer diameter of the mandrel is same as the internal diameter of the finished component. The minor taper is provided on the mandrel for easy removal of the part after forming. The mandrel is made up of Die Steel (AISI D2/D3). The hardness of the finished mandrel lies between 58 to 62 HRC. Stripper ring and toothed ring block are assembled and attached to the flow forming mandrel by a key. Stripper ring is made out of low carbon steel and required to facilitate the removal of the finished tube, and a toothed ring is necessary to ensure rotation of the preform along with the mandrel. Rollers, stripper and toothed rings are made of AISI D2/D3 steel having the hardness of 58~62 HRC. Mandrel, stripper ring and toothed ring are specific for a given flow formed tube. However, rollers can be selected from the available set of standard rollers, considering material and the size of the preform. The tools are loaded heavily during operation and need to follow stringent quality requirements from the raw material stage.

Fig. 2. The flow-forming machine (Make: Leifeld, Germany; Model: ST 56-75 CNC)

After solution annealing of H30 Aluminum alloy, natural aging takes place in ambient conditions. Moreover, preform cannot be subjected to flow forming immediately after solution treatment as it needs to be finish machined to the final dimensions to maintain the desired fit between the flow forming mandrel and preform. Hence, solution treatment of the preform has been carried out in batches of four and kept inside the freezer at 4°C temperature up to 48 hours to minimise the effect of natural ageing. For finish turning of the preform, each preform has been taken out of the freezer and subjected to CNC turning and subsequently stored back in the fridge after finish turning. Thus, flow-forming of the preform is made after 48 hours of solution treatment operation. Rough machining of the preform, subjecting it to solution annealing, carrying out finish machining of solution annealed preform maintaining stringent dimensional and form tolerances and subsequent flow forming of same with a uniform gap of 48 hours to the solution annealing operation was a challenging task. A total number of 136 (2x64 = 128 experiments for DOE equation building and 8 experiments for validation / confirmation) preforms have been realised for this experimental work. Processing of each preform is different from others regarding their three process parameters namely, axial stagger, feed to speed ratio and roller infeed. Experimentations of such a large magnitude using a full-scale production flow forming machine and maintaining such strict process sequence for 136 preform is a significant contribution. One such flow-formed tube is shown in Figure 3 and complete experimental data is tabulated in Table 1.

Fig. 3. A flow-formed tube

Table 1. Experimental Result

No.	AS (mm)	FS(mm/rev)	IF (mm)	Original			Replicate		
				ID (mm)	SB (mm)	OV (mm)	ID (mm)	SB (mm)	OV (mm)
1	9.5	0.5	3	118.310	0.535	0.10	118.278	0.488	0.12
2	9.5	0.6	3	118.290	0.585	0.07	118.268	0.592	0.04
3	9.5	0.7	3	118.253	0.635	0.03	118.193	0.615	0.03
4	9.5	0.8	3	118.148	0.635	0.03	118.095	0.645	0.07
5	9.5	0.5	3.5	118.228	0.560	0.03	118.183	0.505	0.08
6	9.5	0.6	3.5	118.148	0.578	0.03	118.083	0.512	0.04
7	9.5	0.7	3.5	118.083	0.668	0.08	118.070	0.660	0.03
8	9.5	0.8	3.5	118.060	0.688	0.07	118.020	0.690	0.03
9	9.5	0.5	4	118.033	0.558	0.09	118.020	0.493	0.04
10	9.5	0.6	4	118.048	0.638	0.06	117.980	0.615	0.02
11	9.5	0.7	4	118.028	0.708	0.02	118.008	0.703	0.08
12	9.5	0.8	4	117.968	0.720	0.06	117.983	0.760	0.06
13	9.5	0.5	4.5	117.993	0.620	0.04	117.990	0.558	0.03
14	9.5	0.6	4.5	118.025	0.648	0.13	117.940	0.685	0.09
15	9.5	0.7	4.5	117.915	0.705	0.08	117.995	0.708	0.12
16	9.5	0.8	4.5	118.128	0.763	0.10	118.060	0.790	0.07
17	11	0.5	3	118.360	0.540	0.08	118.378	0.493	0.05
18	11	0.6	3	118.238	0.563	0.03	118.243	0.498	0.03
19	11	0.7	3	118.218	0.550	0.04	118.210	0.538	0.03
20	11	0.8	3	118.185	0.608	0.03	118.220	0.600	0.05
21	11	0.5	3.5	118.230	0.565	0.06	118.258	0.523	0.08
22	11	0.6	3.5	118.170	0.633	0.05	118.135	0.580	0.03
23	11	0.7	3.5	118.088	0.673	0.01	118.048	0.625	0.02
24	11	0.8	3.5	118.110	0.705	0.03	118.055	0.688	0.01
25	11	0.5	4	118.108	0.603	0.03	118.103	0.550	0.05
26	11	0.6	4	118.030	0.703	0.06	118.023	0.640	0.03
27	11	0.7	4	118.033	0.723	0.05	118.003	0.648	0.02
28	11	0.8	4	118.018	0.753	0.08	117.983	0.690	0.03
29	11	0.5	4.5	118.038	0.650	0.03	118.010	0.613	0.04
30	11	0.6	4.5	117.978	0.693	0.08	118.008	0.643	0.10
31	11	0.7	4.5	118.010	0.735	0.15	118.008	0.663	0.13
32	11	0.8	4.5	117.958	0.793	0.14	118.020	0.743	0.16
33	12.5	0.5	3	118.335	0.543	0.08	118.363	0.470	0.07
34	12.5	0.6	3	118.293	0.570	0.08	118.350	0.510	0.02
35	12.5	0.7	3	118.280	0.645	0.05	118.320	0.585	0.11
36	12.5	0.8	3	118.180	0.663	0.08	118.243	0.620	0.02
37	12.5	0.5	3.5	118.258	0.505	0.08	118.255	0.480	0.09
38	12.5	0.6	3.5	118.123	0.568	0.02	118.198	0.520	0.06
39	12.5	0.7	3.5	118.068	0.655	0.01	118.198	0.580	0.01
40	12.5	0.8	3.5	118.040	0.715	0.02	118.035	0.652	0.06
41	12.5	0.5	4	118.085	0.548	0.05	118.083	0.488	0.02
42	12.5	0.6	4	118.033	0.633	0.02	118.033	0.605	0.07
43	12.5	0.7	4	118.008	0.660	0.02	118.025	0.638	0.01
44	12.5	0.8	4	117.965	0.695	0.04	117.943	0.683	0.03
45	12.5	0.5	4.5	117.960	0.608	0.03	117.993	0.603	0.09
46	12.5	0.6	4.5	117.975	0.685	0.03	117.948	0.635	0.01

47	12.5	0.7	4.5	117.930	0.745	0.05	117.950	0.710	0.10
48	12.5	0.8	4.5	117.993	0.810	0.10	117.953	0.793	0.03
49	14	0.5	3	118.373	0.590	0.06	118.420	0.528	0.08
50	14	0.6	3	118.348	0.618	0.06	118.410	0.570	0.05
51	14	0.7	3	118.265	0.650	0.07	118.273	0.592	0.08
52	14	0.8	3	118.238	0.703	0.06	118.243	0.645	0.09
53	14	0.5	3.5	118.333	0.590	0.03	118.298	0.525	0.02
54	14	0.6	3.5	118.230	0.618	0.02	118.253	0.585	0.09
55	14	0.7	3.5	118.138	0.667	0.04	118.138	0.645	0.04
56	14	0.8	3.5	118.148	0.715	0.04	118.113	0.645	0.06
57	14	0.5	4	118.120	0.603	0.04	118.130	0.563	0.03
58	14	0.6	4	118.045	0.685	0.01	118.085	0.653	0.05
59	14	0.7	4	117.975	0.770	0.03	117.950	0.705	0.04
60	14	0.8	4	117.945	0.798	0.09	117.953	0.773	0.03
61	14	0.5	4.5	117.975	0.710	0.03	118.033	0.665	0.06
62	14	0.6	4.5	117.985	0.740	0.03	117.958	0.690	0.04
63	14	0.7	4.5	117.968	0.795	0.01	117.935	0.793	0.03
64	14	0.8	4.5	117.960	0.850	0.08	117.960	0.835	0.16

2.2. Measurement of internal diameter, spring-back and out-of-roundness

The three output parameters are: out-of-roundness, spring-back and inner diameter are measured during the experimentation in the following manner. All the measurements have been carried out at the middle cross-section of the shell.

Internal diameter measurements. Internal diameter of the flow formed shell is measured in four angular orientations of the 45 apart., 2 pin bore dial gauge of 10m least count is used for internal diameter measurements. Four readings have been captured in middle cross-section, and an average of these four readings is used in the regression model. **Spring-back measurements.** Spring back of the flow formed tube thickness happens primarily due to the elastic recovery of the created material. It is the difference between the final thicknesses achieved of a shell to the programmed roller-mandrel gap. Spring back has also been measured in 04 points (90° apart) of the middle cross-section of the flow-formed length, and an average of these readings is used.

Out-of-roundness measurements. Procedure adopted for the measurement of the inner diameter is already explained. The out-of-roundness of any cross-section of the flow formed shell is computed from the difference between the maximum internal diameter and minimum inner diameter of the middle cross-section of the shell.

3. COMPLETE FACTORIAL DESIGN OF EXPERIMENTS (DOE)

It is a powerful technique to optimise any manufacturing process or product. Through this method, it is possible to analyse the impact of different factors on the process individually as well as in grouped manner. Flow forming process is affected by roller in-feed (reduction per pass), reduction ratio, feed-speed ratio, roller geometry and axial stagger of rollers. However, three inputs such as roller infeed, feed-speed ratio and axial stagger are found to play a significant role and considered in this study (refer to Figure 4). The impact of those three inputs on predicting three outputs such as out-of-roundness, spring-back, the internal diameter is considered in this study.

Regression models have been developed to build the relationship between inputs and outputs. Four levels for each of the three inputs (refer to Table 2) are considered; thus, $4^3 = 64$ combinations of inputs are considered for the full factorial DOE. Again, all those 64 experiments are repeated once, i.e. finally total 128 shells are fabricated.

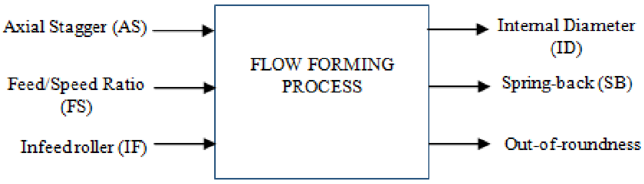


Fig. 4. Inputs and output parameters for the investigated flow forming process

Table 2. Input parameters and their levels

Inputs	Uncoded symbol	Coded symbol	Coded value	Value
Axial Stagger (mm)	AS	X_1	- -	9.5
			- +	11.0
			+ -	12.5
			+ +	14.0
Feed / Speed Ratio(mm/rev)	FS	X_2	- -	0.5
			- +	0.6
			+ -	0.7
			+ +	0.8
Infeed Roller (mm)	IF	X_3	- -	3.0
			- +	3.5
			+ -	4.0
			+ +	4.5

Five numbers of validation experiments were also carried out. Parameters combinations for these five trials were selected within the limit of the experimental zone, but other than the combinations as chosen in first 64 trails. Moreover, to check the validity of the developed model outside, but near vicinity of the experimental zone, another three numbers of experiments were conducted with parameter combinations which lie outside the first ranges.

DOE and multiple regression analysis are applied to the collected data. Through this, a single equation relating one output (say Y) as a function of three inputs (X_1, X_2, X_3) is derived. The equations will look like the following:

$$Y = a_0 + a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_1 x_2 + a_5 x_2 x_3 + a_6 x_1 x_3 + a_7 x_1 x_2 x_3 \tag{1}$$

The a_0 term and the a_1-a_7 coefficients of the models are to be estimated using experimental data through DOE. In this study also three inputs and three responses are considered.

4. RESULTS OF DOE

The following equations are obtained using regression corresponding to the experimental data presented in Table 1.

$$\begin{aligned} ID = {} & 119.69 - 0.0081 \times AS - 2.77 \times FS - 0.411 \times IF + 0.076 \times AS \times FS \\ & + 0.0134 \times AS \times IF + 0.635 \times FS \times IF - 0.0301 \times AS \times FS \times IF \end{aligned} \tag{2}$$

$$\begin{aligned} SB = {} & -0.757 + 0.015 \times AS - 0.87 \times FS - 0.0675 \times IF \\ & + 0.0341 \times AS \times FS + 0.2497 \times FS \times IF \end{aligned} \tag{3}$$

$$\begin{aligned} OV = {} & 1.44 - 0.0807 \times AS - 2.66 \times FS - 0.395 \times IF + 0.166 \times AS \times FS \\ & + 0.2876 \times AS \times IF + 0.771 \times FS \times IF - 0.0486 \times AS \times FS \times IF \end{aligned} \tag{4}$$

4.1. Prediction of internal diameter (ID)

Test of significance for regression model and individual model coefficients are assessed using ANOVA and is presented in Table 3 for the first output (ID). All the three inputs parameters have a significant contribution to the model. Out of four interaction terms, two interaction terms are found to be statistically significant, and other two are insignificant. However, none of these irrelevant terms is eliminated from the model as P-value for two-way interaction terms is found to be significant. Moreover, three-way interaction term is found to be significant. R^2 = 95.99 and R^2 (adj) =92.04 are close enough suggesting the influence of all the factors on ID is existing, and the model is good enough to predict the response. In Table 3, the terms DF, Seq. SS, Adj. SS, Adj. MS and P represent the degrees of freedom, sequential sum error, the adjusted sum of square, adjusted mean square and probability values, respectively. It is important to note that the model has 95% confidence level.

Table 3. ANOVA results for internal diameter (ID)

Source	DF	Seq SS	Contrib. (%)	Adj SS	Adj MS	F	P
Model	63	1.596	95.99	1.596	0.0253	24.32	<0.001
Linear	9	1.458	87.71	1.458	0.1620	155.53	<0.001
AS	3	0.126	7.57	0.126	0.0419	40.25	<0.001
FS	3	1.132	68.10	1.132	0.3774	362.3	<0.001
IF	3	0.200	12.04	0.200	0.0667	64.04	<0.001
2-Interactions	27	0.086	5.18	0.086	0.0031	3.06	<0.001
AS*FS	9	0.014	0.87	0.014	0.0016	1.54	0.153
AS*IF	9	0.012	0.77	0.012	0.0014	1.37	0.222
FS*IF	9	0.059	3.54	0.059	0.0065	6.28	<0.001
3-Interactions	27	0.052	3.10	0.052	0.0019	1.83	0.025
AS*FS*IF	27	0.052	3.10	0.052	0.0019	1.83	0.025
Error	64	0.067	4.01	0.067	0.0010		
Total	127	1.663	100.00				

Figures 5 and 6 show the main and interaction effect plots for predicting ID. Following observations are made from this result.

a) The model is susceptible to the feed/ speed ratio (FS). The internal diameter increases with the decrease in FS value. Therefore, a higher level of FS is preferred to minimize the increase in inner diameter. The low-level FS reduces the axial feed rate of the rollers, leading to retarded axial plastic deformation compared to radial strain and results in an increase in ID.

b) Infeed has the inverse relationship between the internal diameter, and axial stagger is found to have a direct connection with ID. With the increase in AS, resultant roller attack angle decreases. Such decrease in roller attack angle leads to lower S/L values, thus, resulting in the diametral growth of flow formed tubes.

Fig. 5. Main effects plot for internal diameter.

From Figure 6, significant interactions of the three variables exist between FS and IF, AS and IF. The communication between FS and IF is more compared to that between AS and IF. However, for the highest level of FS, no cooperation exists between the FS and IF.

a) Therefore, to minimize the change in internal diameter, present inclusive manufacturing procedures forecasts to consider the higher value of FS, the larger value of infeed roller and lower axial stagger.

Residual plot for the internal diameter (ID) is presented in Figure 7, which shows a normal distribution plot and a majority of them is lying near to the mean value having zero residues.

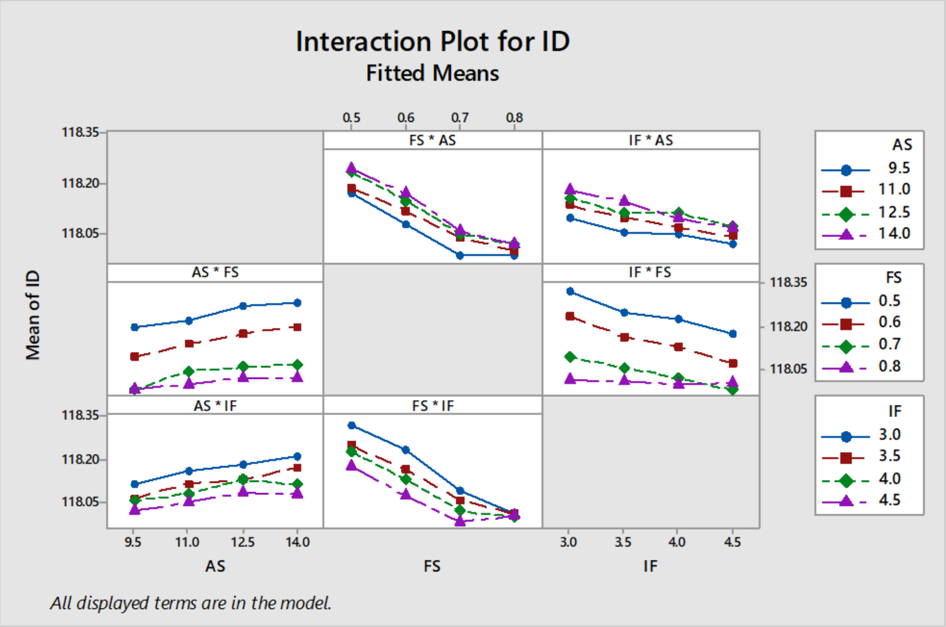


Fig. 6. Interaction plot for internal diameter

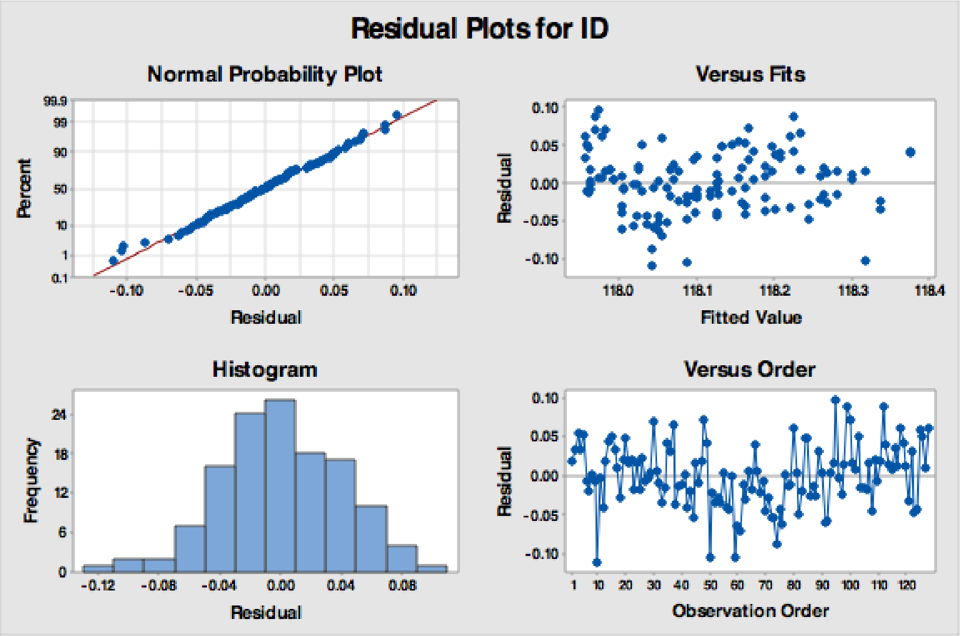


Fig. 7. Residual plot for the response variable internal diameter (ID)

4.2. Prediction of spring-back (SB)

For a better controllability of flow formed tube thickness, SB should also be as low as possible. Regression analysis along with ANOVA has been carried out (refer to Table 4) to understand the input conditions for the lowest value of SB. The contribution of the individual factors alone is seen to be higher than that of their interacted terms. Also, the contribution made by feed-speed ratio and infeed is the maximum. Error in building the model has been found to be 19.71%; it is because that none of the interaction terms is found to be significant. Equation (3) represents the relationship between the SB and three inputs. Figures 8 and 9 show the main and interaction effects of the model.

Table 4. ANOVA results for the spring-back (SB)

Source	DF	Seq SS	Con-trib. (%)	Adj SS	Adj MS	F	P
Model	63	0.874	80.29	0.8746	0.0138	4.14	<0.001
Linear	9	0.758	69.64	0.7585	0.0842	25.13	<0.001
AS	3	0.021	1.99	0.0217	0.0072	2.16	0.102
FS	3	0.376	34.57	0.3765	0.1255	37.43	<0.001
IF	3	0.360	33.07	0.3602	0.1201	35.8	<0.001
2-Inter actions	27	0.078	7.20	0.0784	0.0029	0.87	0.653
AS*FS	9	0.008	0.77	0.0083	0.0009	0.28	0.979
AS*IF	9	0.018	1.74	0.0189	0.0021	0.63	0.77
FS*IF	9	0.051	4.69	0.0510	0.0056	1.69	0.109
3-Inter actions	27	0.037	3.46	0.0376	0.0014	0.42	0.993
AS*FS*IF	27	0.037	3.46	0.0376	0.0014	0.42	0.993
Error	64	0.214	19.71	0.2146	0.0034		
Total	127	1.089	100.00				

Following observations are made from this study:

a) Axial stagger has a low significant role on spring-back. Effect of Infeed is found to be more significant than the feed-speed ratio. The dependency of spring-back on infeed and the feed-speed ratio is well understood from the fact that with the increase in roller infeed the absolute value of plastic deformation increases which leads to higher elastic recovery after removal of deformation load. Similarly, deformation rate increases with the increase in feed-speed ratio, resulting in high elastic recovery time after forming.

b) The difference between the $R^2 = 80.29\%$ and the R^2 (adj) = 60.90% is high, suggests that there exists less number of significant terms in the model and accuracy in prediction will be low.

c) None of the interaction terms is found to be statistically significant. However, the contribution of FS*IF is found to be relatively higher.

d) From the perspective of inclusive manufacturing, flow forming process engineer will primarily focus on feed-speed ratio and infeed roller, and he/she will select lower levels of three input parameters to minimise the spring-back (SB).

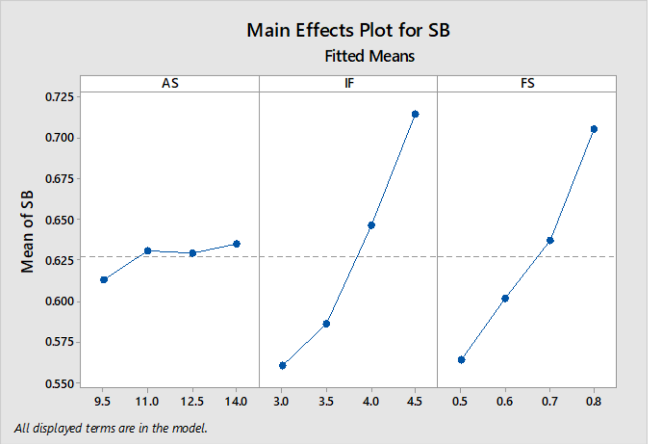


Fig. 8. Main effects plot for Spring-back (SB).

Fig. 9. Interaction plot for Spring-back (SB)

4.3. Prediction of out-of-roundness (OV)

Results of ANOVA for prediction of out-of-roundness (OV) are presented in Table 5. From, the results, it is evident that 3-way interaction term makes the highest contribution. Two linear terms FS and IF and all the interaction terms are found to be significant. Since the three-way interaction term is significant, all the three input variables are essential for the model. R^2 and R^2 (adj) values are found to be 82.15% as 64.58%.

Table 5. ANOVA results for out-of-roundness (OV)

Source	DF	Seq SS	Contrib(%)	Adj SS	Adj MS	F	P
Model	63	0.195	82.15	0.195	0.0031	4.68	<0.001
Linear	9	0.062	26.26	0.062	0.0069	10.46	<0.001
AS	3	0.002	0.90	0.002	0.0007	1.08	0.363
IF	3	0.047	20.04	0.048	0.0159	23.96	<0.001
FS	3	0.013	5.31	0.013	0.0042	6.34	0.001
2-Inter actions	27	0.081	33.92	0.081	0.003	4.51	<0.001
AS*IF	9	0.026	10.98	0.026	0.0029	4.38	<0.001
AS*FS	9	0.019	8.30	0.02	0.0022	3.31	0.002
IF*FS	9	0.035	14.63	0.035	0.0039	5.83	<0.001
3-Inter actions	27	0.052	21.97	0.052	0.0019	2.92	<0.001
AS*IF* FS	27	0.052	21.97	0.052	0.0019	2.92	<0.001
Error	64	0.042	17.85	0.042	0.0007		
Model	63	0.195	82.15	0.195	0.0031	4.68	<0.001

Figure 10 shows the main effect plot and Figure 11 represents the interaction effect of the inputs on out-of-roundness. Few significant observations are from this analysis are presented below:

a) Axial stagger has almost no impact on the out-of-roundness on its own. Out-of-roundness decreases with the increase in speed/feed ratio for the first three levels, but it suddenly decreased in the fourth level. Therefore, it is wiser to maintain the speed/feed ratio between the first three levels.

b) For initial three levels of feed-speed ratio, increase in feed rate results into better synchronization between axial and radial plastic deformation which leads to a lower value of out-of-roundness. However, with the highest level of feed-speed ratio, roller moves faster over the mandrel, denying uniform plastic deformation. Such phenomenon results into sudden increase in out-of-roundness. Similarly, the low value of feed-speed ratio ensures consistent strain between rollers and mandrel. However, a very high amount of the feed-speed ratio, plastic deformation is retarded and highly strained surface is produced. Such phenomenon finally leads to a sudden jump in out-of-roundness.

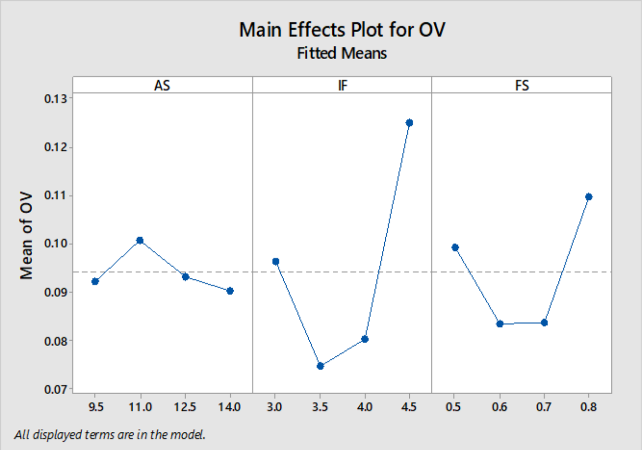


Fig. 10. Main effects plot for the response out-of-roundness (OV)

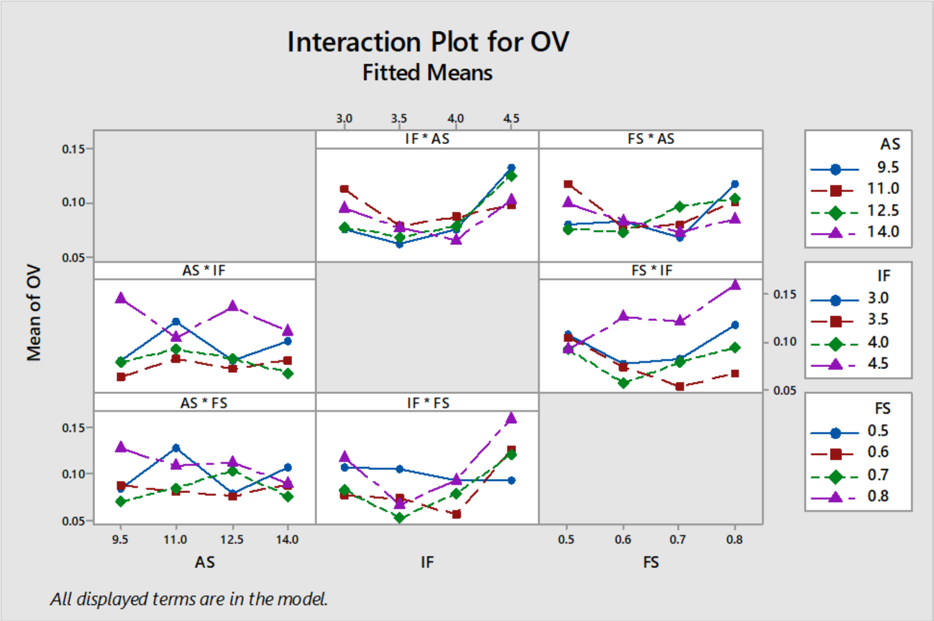


Fig. 11. Interaction plot for the response out-of-roundness (OV)

c) Minimum out-of-roundness is achieved for the fourth level of AS when IF changes between the first two levels. Whereas, maximum out-of-roundness is seen for the third level of AS with the IF value varying from 4.0mm to 4.5mm.

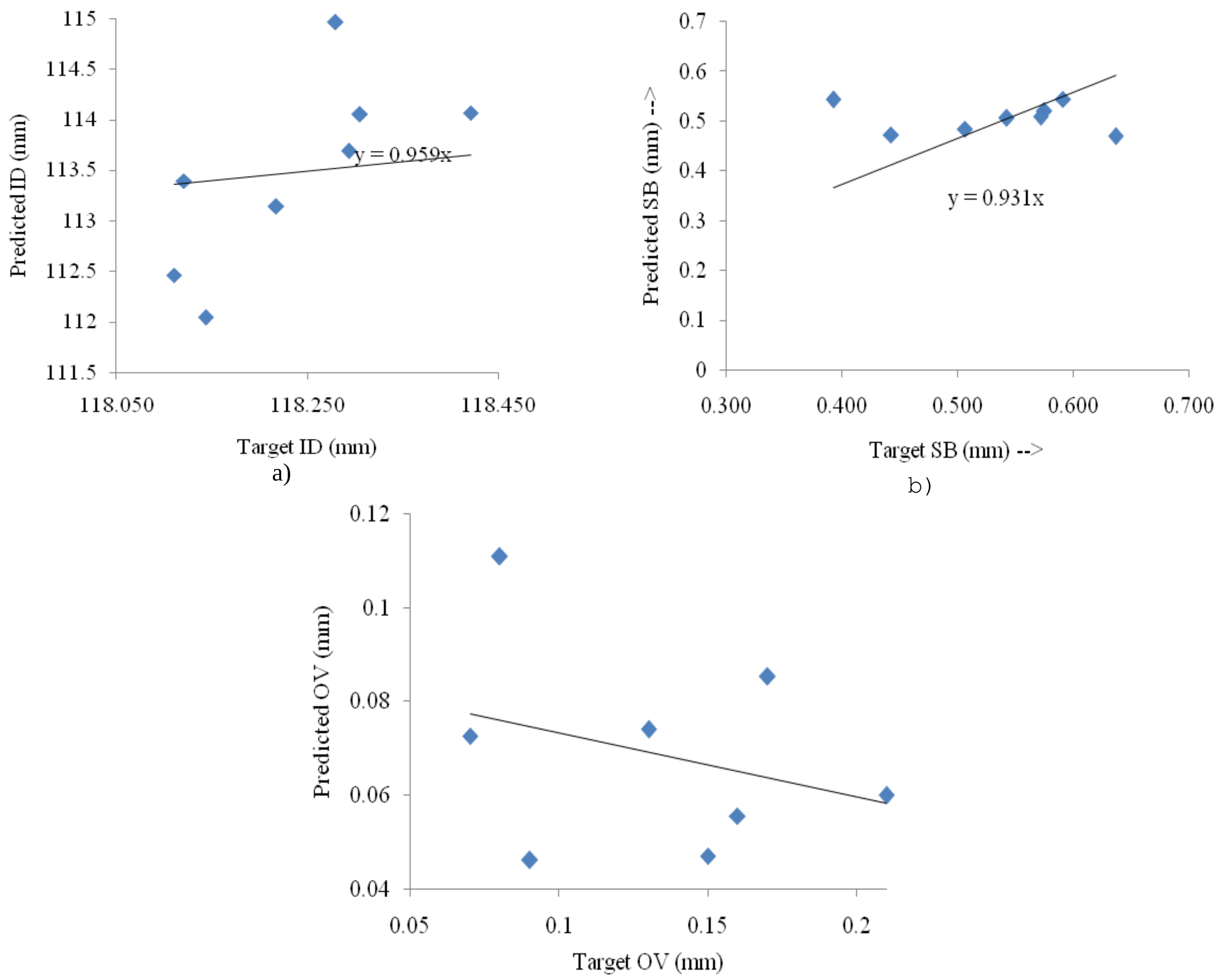
d) Shallow value of out-of-roundness is possible with the second and third level of IF. This manufacturing analytics method is beneficial in ascertaining the complex phenomena relating to out-of-roundness in the flow forming process.

4.4. Validation of the regression models

Developed regression models are used to obtain the outputs against eight input sets (refer to Table 6). Five input sets correspond to the input combinations within the limits of the experimental zone but other than the combinations used to build the statistical models. However, last three are outside the pre-selected bounds of the input parameters. For each input set, response versus target values is shown in Figure 12 and a best-fit straight line is drawn. In the ideal case, the best-fit line should pass through the origin having 45^0 slopes. However, for all the three outputs best-fit lines are deviating slightly from the perfect line. It may be due to several reasons. We believe that out-of-roundness is a complex phenomenon and it is very difficult to derive empirical relationship for the same. Moreover, some of the inputs such as roller force, existing out-of-roundness of the preform, roller entry angle are also responsible for the model and consideration of them might improve the model accuracy. Measurement errors, simplification of the model are some of the other factors.

Table 6. Test data of the flow-forming process

Expt No.	AS (mm)	FS (mm/rev)	IF (mm)	OV (mm)	SB (mm)	ID (mm)
1	12	0.55	3.7	0.21	0.507	118.218
2	12	0.75	4.2	0.13	0.443	118.110
3	10	0.65	3.2	0.15	0.575	118.294
4	10	0.72	3.4	0.09	0.543	118.121
5	12	0.65	3.2	0.16	0.572	118.305
6	9	0.4	2.8	0.08	0.393	118.421
7	9	0.9	2.5	0.17	0.591	118.279
8	15	0.45	4.8	0.7	0.637	118.143



a)

b)

c)

Fig.12. Predicted versus target values of three responses

5. CONCLUSIONS

Manufacturing of thin-walled precision H30 Al-tubes is a tricky one. The fabrication process for the realisation of these kinds of products needs to be automated. During the establishment of input parameters through experimentation or trial and error approach, manufacturing engineers keep changing inputs till target dimension or tolerance is reached. Once a target is achieved, further refinement of input parameters is usually avoided to minimise lead time and cost associated with new product development. Thus the scope for optimization of process parameters is lost, resulting in products with acceptable quality only. However, in present study predicting model is not only capable bringing response within acceptable limit but also provides the optimal value. Therefore, better products with improved quality without compromising the productivity of the process are achieved.

Here, an inclusive manufacturing approach using regression analysis is presented for fabricating thin Al-tubes through cold flow forming. Regression equations for three outputs (internal diameter, spring-back and out-of-roundness) are built individually as a function of the feed-speed ratio, axial stagger and roller infeed. Change in inner diameter, spring-back and out-of-roundness are drawbacks of the flow forming process. Therefore, flow former's aim is to minimize all of these three variables through an optimal choice of three inputs as specified above. Significant findings are listed below.

a) It has reduced the human error and operators can identify beforehand the achievable manufacturing tolerance. In turn, it will help to minimize the production time and cost. Also, it will reduce the wastage of raw material.

b) A set of multi-variable input-output relationships for cold flow forming of H30 Aluminum alloy tubes is built. Such relations can be used as a tool for selection of initial process parameters without carrying out trial experiments.

c) Further, the set of derived relations can also be used as a knowledge base for automation of the process and to obtain the optimized response by selection of suitable combinations of various levels of the input parameter.

d) The internal diameter changes inversely with the feed-speed ratio (FS) and roller infeed (IF). However, it is directly proportional to the axial stagger (AS). Therefore, minimum change in internal diameter is possible with higher levels of FS and IF and lower levels of AS. Feed-speed ratio (FS) is found to be the most significant among the three inputs in this regard.

e) The spring back (SB) of thin H30 Al-tubes is directly proportional to all the three inputs. Therefore, the minimum value of spring-back is achieved with lowest levels of all the three inputs. However, its dependency on roller axial stagger (AS) is negligible.

f) A complicated relationship exists between the out-of-roundness with the inputs. The out-of-roundness of the tubes was found to be dependent on all the three inputs. However, lowest out-of-roundness is achieved with 3.5 mm of roller infeed and 0.7 mm/rev of feed-speed ratio. Also, increase in axial stagger resulted in a decrease in out-of-roundness.

g) Though the established relationships are good enough in predicting the output of flow forming trials, there is scope for improving the accuracy of the developed model, especially for out-of-roundness. Several additional inputs such as roller force, existing out-of-roundness of the preform, roller entry angle etc. need to be considered to build an improved predictive model.

h) Till-now, researchers have neglected the influence of axial stagger of rollers on the process since they have used only one roller [23]. However, we have used three rollers and impact of axial stagger is also observed.

i) The present work is an advanced study of the work carried out by Komaraiah et al. [24]. They have considered one output. However, three outputs have been considered in this study. Moreover, four-level DOE has been considered in comparison to three-level three factors study made by Komaraiah et al. [24]. It has resulted in the improvement of the accuracy.

Following extensions of the work is possible.

a) Development of an expert system based on soft computing techniques for modelling the flow forming process.

b) Comparison between the regression and soft computing-based models for fabricating the tubes of tough materials.

6. AKNOLEDGEMENT

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