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Experimental investigation on flow-forming of AA6061 alloy—A Taguchi approach

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ABSTRACT

An annealed AA6061 aluminum tubing preform was cold flow-formed into a seamless tube. A multiple pass flow-forming was performed. In this investigation, the influence of the various flow-forming process parameters on the percentage elongation (%*D*) has been analyzed. The parameters considered are the speed of the mandrel, *S* (rpm), the depth of cut, D_c (mm) and the feed, *F* (mm/min). The effects of these input parameters on the response, percentage elongation (%*D*) have been critically analyzed using Taguchi method. It has been found that the depth of cut is the most important process parameter affecting the percentage elongation. The flow-forming process produced a maximum percentage elongation of 18% when the process parameters were set at their optimum values.

1. Introduction

Flow-forming is a chipless metal-forming process which employs an incremental rotary point deformation technique. In flow-forming, the wall thickness of a tube or preform is reduced and the length is increased without changing the internal diameter. Flow-forming is used in the production of cylinders, flanged components, axi-symmetric sheet metal parts, seamless tubes for high-strength aerospace, missile applications, etc. Many experimental- and analytical-based research works have been carried out by many researchers. Kalpackcioglu (1964) worked on the power spinning of tubes. Singhal and Das (1987) performed an experimental investigation in the shear spinning of long tubes. Rajan and Narasimhan (2001) investigated the development of defects during flow forming of high strength thin wall steel tubes. To meet the structural strength requirements, components for aerospace applications are usually manufactured through cold working. Flow-forming offers excellent dimensional tolerances and it improves the mechanical properties of the product considerably.

Many process factors affect the effectiveness of the flow-forming process. The main purpose of this paper is to establish the significant factors that influence the plastic flow of AA6061 alloy during the flow-forming process. This can be determined through a series of experiments. However, such experiments will be expensive and time-consuming. Design of experiment (DOE) techniques like the Taguchi method, the response surface methodology, etc. can optimize process parameters with minimum experimental runs. Enormous amount of research has been conducted for determining optimal process parameters of various manufacturing processes. Der Ho and Mao Sheng (2004) used Taguchi method to develop a robust design for the magnesium alloy die casting process. Alauddin et al. (1997) used response surface method to predict tool life in end milling. Dhavlikar et al. (2003) used Taguchi and response sur-

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face method to optimize a centerless grinding process. Tsao and Hocheng (2004) used Taguchi method to determine the delamination associated with various drill bits in drilling of composite material. However, no work has been reported on the modeling of flow-forming process using DOE techniques. The present investigation is on the optimization of process parameters of flow-forming process for maximum deformation using Taguchi method.

2. Experimental work

2.1. Flow-forming process

Flow-forming is an advanced, near net shape, hot and cold working process for manufacturing seamless, dimensionally precise tubular and other rotationally symmetrical products. Compression is given to the outside diameter of a cylindrical preform, attached to a rotating mandrel by a combination of axial and radial forces using a set of three or four rollers that are simultaneously moved along the length of the rotating preform. These loads, when it reaches above the yield strength of the preform, flow the material plastically in both the radial and the axial directions. As the process produces localized deformation, much greater deformation of the material can be achieved with lower forming forces as compared with other processes.

Depending on the direction of axial flow of the perform material during the process, flow-forming process can be classified into two types namely forward flow-forming and backward flow-forming. In forward flow-forming, the material flows in the same direction as that of the traversing rollers. In backward flow-forming, the preform material flows under the roller in the opposite direction of the roller towards the tailstock end of the mandrel (Lai and Lee, 1992; ASM, 1988).

2.2. Equipment

The present investigation was performed on a four-axis CNC flow-forming machine with a single roller. The flow-forming machine used in this research work is shown in Fig. 1. The roller travels parallel to the axis of the mandrel with a feed rate V (mm/min) and reduces the wall thickness of the preform when a depth of cut D_c (mm) is given. Compressive and axial loads are given by the roller, which is fitted to the arm of the machine. The feed rate and depth of cut are maintained by four high-torque servomotors fitted to the four arms of the machine and these servomotors are driven by a hydraulic power pack. The depth of cut is given by maintaining the gap between the mandrel and the roller lesser than the thickness of the preform. The preform is reduced to a final thickness by elongating it without change in the inside diameter of the tube. Due to volume constancy, this reduction in thickness of the preform leads to an increase in length of the tube. It is desired to produce seamless tubes of maximum percentage elongation ratio and good strength with minimum or no surface damage. The percentage increase in length (percentage elongation), %D of the preform is obtained by $(L_2-L_1/L_1)\times 100$ where L_1 is the initial length of preform and L_2 is the length of the preform after a flow-forming cycle. Fig. 2 shows an AA6061 alloy tube produced by flow-forming process.

Fig. 1 – Flow-forming machine with single roller arrangement.

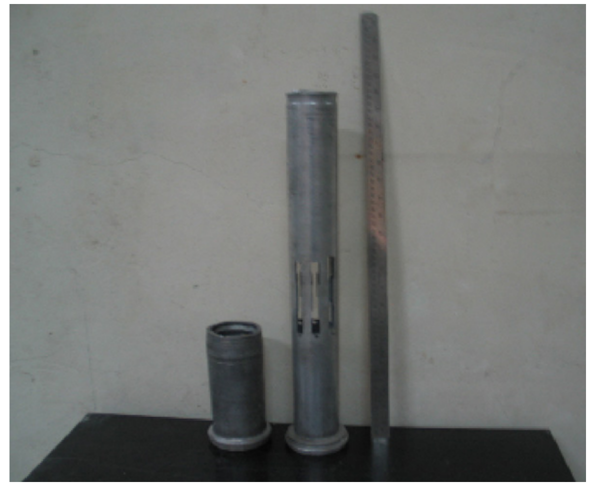

Fig. 2 – Flow-formed AA6061 tube sample.

2.3. Material

The material used for the present investigation is AA6061 alloy. The major alloying elements are Al–1Mg–0.6Si–0.25Cu–0.2Cr. AA6061 has moderate strength, excellent corrosion resistance and high plane strain fracture toughness. The main components of heat treatable AA6061 alloy are Mg and Si. The alloy derives its strength from the precipitation-hardening phase Mg_2Si. AA6061 has an ultimate tensile strength of 310 MPa, yield strength of 275 MPa and hardness of around 107 Hv. AA6061 has excellent joining characteristics and has good acceptance for coatings. Its excellent mechanical properties have made it possible to be used in aircraft fittings, couplings, marine fittings, brake pistons, hydraulic pistons, valves and valve parts, bike frames, etc.

2.4. Preform design

The preform was designed based on two factors namely maximum possible deformation and constant volume principle. These preforms were manufactured by hot forging leaving some machining allowance on external diameter and then machined to fit in the mandrel. The preform was then annealed at a temperature of 416 °C and quenched in water. The flow-forming mandrel is made of tool steel. A slight taper is given in the mandrel for easy ejection of the product.

3. Plan of experiments

The present investigation uses Taguchi method, which is a powerful design of experiments tool. This method provides a simple, efficient and systematic approach to determine optimal machining parameters. Conventional experimental design methods are too complex and expensive. A large number of experiments have to be carried out to study the process. Taguchi method uses an orthogonal array to study the entire process with only a small number of experiments. Moreover, traditional experimentation involves one-factor-at-a-time experiments, wherein one variable is changed while the rest are held constant. The major disadvantage of this method is that it fails to consider any possible interactions between the parameters. An interaction is the failure of one factor not to produce the same effect on the response at different levels of a second factor varying. It is also not possible to study all the factors involved in the process and to determine their main effects (i.e., the individual effects) in a single experiment. Taguchi technique overcomes all these drawbacks. Taguchi method is used for optimizing process parameters and identifying the optimal combination of factors for the desired responses (Ross, 1989; Garcia-Diaz, 1995; Montgomery, 2001; Tarang, 1998; Cox, 2000; Phadke, 1989; George et al., 2004). The steps involved are (George et al., 2004)

1. Identification of the response functions and the process parameters.
2. Determination of the number of levels for the process parameters and possible interaction between them.
3. Selection of the appropriate orthogonal array.
4. Selection of the optimum level of process parameters through ANOVA analysis.
5. Performing a confirmation experiment to verify the optimal process parameters.

The input parameters chosen for the experiments are (a) depth of cut, D_c (mm), (b) speed of the mandrel, S (rpm) and (c) feed, F (mm/min) while the response function is the percentage elongation, $\%D$, attained by the preform after a cycle of flow-forming experiment.

Trail runs were carried out by varying one of the process parameters whilst keeping the rest of them at constant values. The working range was decided upon by measuring the achievable percentage elongation on the crack-free preforms. The range and the number of levels of the design parameters are given in Table 1. The flow-forming experiment was performed as per the condition dictated by design matrix, developed through Taguchi technique. The percentage elongation of the preform was measured with a digital vernier caliper of ±0.05 mm accuracy, for each experimental run. During the experiment, the mandrel was well lubricated with graphite paste.

Table 1 – Parameters and their levels

Symbol	Parameters	Level 1	Level 2	Level 3
D_c	Depth of cut (mm)	1.0	1.5	2.0
S	Speed (rpm)	200	250	300
F	Feed (mm/min)	50	75	100

3.1. *Developing the design matrix*

In the present analysis, an L9 orthogonal array with three columns and nine rows is used. This array can handle three-level process parameters. Therefore, only nine experiments are required to study the entire flow-forming process. The experimental layout for the present work using the L9 orthogonal array is shown in Table 2. The coded value 1 represents the level 1, 2 represents the level 2 and 3 represents the level 3.

A statistical analysis of variance (ANOVA) is performed to identify the process parameters that are statistically significant. Based on ANOVA the optimal combination of the parameters is predicted.

4. Analysis of experimental results

The experimental results are analyzed, to see the main effects and the difference between the main effects of level 1 and level 2 and between level 2 and level 3 of the variables on the percentage elongation attained by the preform after a cycle of flow-forming experiment. In the present work, only single run is performed for each of the nine experiments. As the main objective of the present research is to minimize the cost and time of the flow-forming process, the above-mentioned approach has been adopted. However, in situations where there is a feasibility to perform multiple runs for each of the experimental run provided by the design matrix, the Taguchi analysis can be performed by using either the standard deviation method or by S/N ratio analysis. In the present analysis, considering the constraint (cost and time) mentioned above, Taguchi analysis is performed based on “average-of-results” methodology, which is described below.

Table 2 – Experimental layout using L9 array

Experiment number	Parameter level			Experimental result for $\%D$
	D_c	S	F	
1	1	1	1	3
2	1	2	2	4
3	1	3	3	2
4	2	1	2	3
5	2	2	3	5
6	2	3	1	4
7	3	1	3	12
8	3	2	1	18
9	3	3	2	16

Table 3 – Main effects and their difference on the percentage elongation

Factors	Level 1 (L_1)	Level 2 (L_2)	Level 3 (L_3)	Difference between levels		
				L_2-L_1	L_3-L_1	L_3-L_2
D_c (mm)	3	4	15.3	1	12.3	11.3
S (rpm)	6	9	7.3	3	01.3	−01.7
F (mm/min)	8.3	7.6	6.3	−.7	−02.0	−01.3

In order to estimate the main effects and their differences, first the overall mean value of the observations for the experimental region is calculated. For example, the overall mean of the percentage elongation is given by the following equation (Phadke, 1989):

$$\text{mean}\,(\%D) = \frac{\sum_{i=1-9} (\%D)}{9} = 7.4 \quad (1)$$

The main effect of a parameter level, for example, depth of cut, D_c at low level (i.e., $D_c = 1$ mm), on %D is given by the following equation (Phadke, 1989):

$$\text{mean}\,(\%D)_{D_c=1\,\text{mm}} = \frac{\%D_1 + \%D_2 + \%D_3}{3} = 3 \quad (2)$$

The main effects and their difference associated with the percentage elongation are given in Table 3.

The change of depth of cut from

(1) 1–1.5 mm, results in an increase in main effects of percentage elongation from an average value of 3–4 and
(2) 1.5–2 mm, results in an increase in the percentage elongation from an average value of 4–15.3.

In the flow-forming process, the preform is spun with a mandrel and the roller is traversed axially, making the metal to flow in the radial, axial and tangential directions through the gap between the roller and the mandrel. Thus the depth of cut plays an important role in the plastic deformation process. Too small a depth of cut leads to strain hardening of the preform and it fractures before arriving at the desired length. A heavier depth of cut exerts more pressure per unit area of the deformation zone on the preform. Light reductions deform only the surface of the preform resulting in work hardening of the material. Due to this, uneven strength exists between the surface of the tube and the interior of the tube. This unevenness in strength results in crack formation in the flow-formed tube. However, if the depth of cut is more, in each pass, the roller faces comparatively new deformation zone and more deformation-zone-area resulting in more deformation as well as good surface characteristics. However, there is a limit in the level of the maximum reduction per pass that can be applied on the preform. This is because of the fact that the stresses induced during the process should be greater than the yield strength and lesser than the fracture strength of the material. For the present case, a depth of cut of 2 mm yielded maximum deformation without fracture.

The change of speed of the mandrel from 200 to 250 rpm (level 1 to level 2), results in the increase in main effects of the percentage elongation from an average value of 6–9. However, the change of speed from 250 to 300 rpm has reduced the percentage elongation. Too small speed leads to sticking of the preform with the rollers resulting in less deformation and increased strain hardening effects and too large speed leads to vibration of the machine tool leaving a poor surface finish and reduced deformation rate. High speeds increase the temperature of the preform considerably in the plastic deformation zone and the generated heat has a significant influence on the deformation rate. The sudden increase in heat of the preform produces excessive adiabatic heating resulting in plastic instability of the preform leading to failure of the preform material.

The change of feed from 50 to 75 mm/min (level 1 to level 2) decreases the percentage elongation from 8.3 to 7.6. The change of feed from 75 to 100 mm/min (level 2 to level 3) decreases the percentage elongation further from 7.6 to 6.3. Too high a feed rate makes the roller travel faster through the preform and due to insufficient time, the plastic deformation process is affected. Synchronization between the feed and speed of the mandrel is needed for maximum deformation. In the present investigation it is found that better results are obtained for a speed of 250 rpm and a feed of 50 mm/min.

Fig. 3 shows the linear graphs of the main effects and their variation between levels of the parameters on the percentage elongation. The relative slope of the linear graphs indicates significance of the parameters. Here, the slope of the graph showing the influence of depth of cut is more compared to other graphs. The main effects and their difference associated with the percentage elongation are given in Table 3. Hence, from Fig. 3 and from Table 3, it can be concluded that the depth of cut is the most significant parameter of percent-

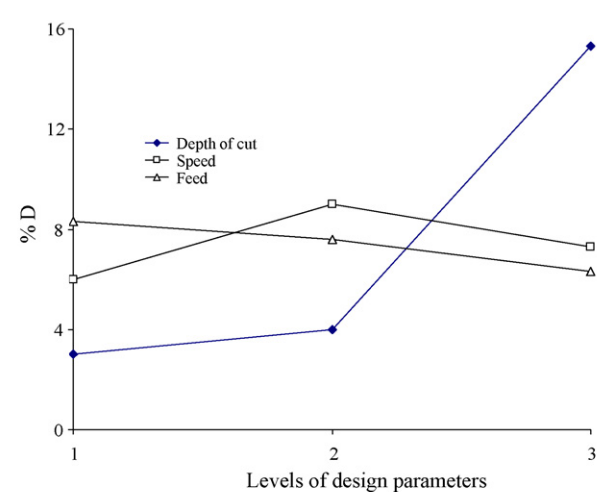

Fig. 3 – Graph showing the main effect of the design parameters on percentage elongation.

Table 4 – Analysis of variance (ANOVA)

Factor	d.f.	Sum of squares, *S*	Variance, *V*	*F*-ratio, *F*	Pure sum, *S*	Percent (%)
D_c (mm)	2	281	140	97	278	92
S (rpm)	2	13	6	5	10	04
F (mm)	2	6	3	2	3	01
Others\error	2	3	1			03
Total	8					100

Table 5 – Optimum conditions for maximum percentage elongation

Factors	Level description	Level	Contribution
D_c (mm)	2	3	7.8
S (rpm)	250	2	1.5
F (mm/s)	50	1	0.8

age elongation followed by speed of the mandrel and feed rate.

The results of ANOVA for the response function, percentage elongation are given in Table 4. Comparison of percentage contributions of the parameters indicates that the depth of cut is the most significant parameter influencing the percentage elongation followed by the speed of the mandrel and the feed. This agrees to the plot in Fig. 3.

5. Confirmation test

A confirmation experiment is needed to determine the optimum conditions and to compare the results with the expected conditions (Savas and Kayikci, 2007). Confirmation run was performed to validate the model generated. For a speed of 183 rpm and a depth of cut of 1 mm, a percentage elongation of 4.9% was achieved which is within the range of the model developed. Table 5 gives the optimum conditions for attaining maximum percentage elongation. It reveals that for maximum percentage elongation, the depth of cut should be at level 3, the speed of the mandrel should be at level 2 and the feed should be at the minimum level. The model predicts an optimum value of 18% for %*D*. Since the optimum combination is one of the experimental runs (experiment number 8 in Table 2) an extra confirmation run is not required. The total contribution from all the factors is 10.3. It gives the contribution that a factor has made to improve the expected outcome. The current grand average of performance is 7.4. It is the arithmetic average of all trial average.

6. Conclusions

The process parameters that affect the flow-forming process have been studied using Taguchi technique. The variables affecting the percentage elongation according to their relative significance are the depth of cut, the speed of the mandrel and the feed, respectively. The optimum forming condition is said to be at depth of cut = 2mm, speed = 250 rpm, and feed = 50 mm/min. It has been shown that, forming parameters set at their optimum levels can ensure significant improvement in the response function.

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