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Surface roughness prediction of flow-formed AA6061 alloy by design of experiments

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ABSTRACT

Design of experiments has been used to study the effects of the main flow-forming parameters such as the speed of the mandrel, the longitudinal feed, and the amount of coolant used on the surface roughness of flow-formed AA6061 tube. A mathematical prediction model of the surface roughness has been developed in terms of the above parameters. The effect of these parameters on the surface roughness has been investigated using response surface methodology (RSM). Response surface contours were constructed for determining the optimum forming conditions for a required surface roughness. The developed prediction equation shows that the longitudinal feed rate is the most important factor that influences the surface roughness. The surface roughness was found to increase with increase in the longitudinal feed and it decreased with decrease in the amount of the coolant used. The verification experiment carried out to check the validity of the developed model predicted surface roughness within 6% error.

1. Introduction

Flow-forming is a chipless metal forming process which employs an incremental rotary point deformation technique. In flow-forming of tubes, 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 and missile applications, etc. There are several defects in flow-forming, such as build up and bell mouthing, diametrical growth, surface cracks, bad surface finish, etc. The surface finish of machined parts plays a considerable role in the wear resistance and fatigue strength. In order to know surface quality of flow-formed tubes in advance, it is necessary to employ statistical methods to predict surface roughness as a function of operating conditions. Yang and Tang (1998) have used Taguchi method to find the optimal cutting parameters for turning operation. Choudhury and El-Baradie (1997) have used response surface methodology for predicting surface roughness of high strength steel. Gokler and Ozanozgu (2000) investigated the surface roughness achievable for 1040, 2379 and 2738 steel materials for wire EDM process. Thomas et al. (1997) used a full factorial design to investigate the effect of cutting tool parameter on the surface roughness of carbon steel. However, very little work has been reported on the flow-forming process. Kalpackcioglu (1964) worked on the power spinning of tubes. Singhal and Das (1987) performed an experimental investigation in the shear spinning of long tubes. An extensive literature survey revealed that no work has been reported on the production of AA6061 tubes using flow-forming principle and their quality aspects.

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Nomenclature

A	first factor or input variable investigated—feed in mm/min
Adeq precision	adequate precision
Adj. R^2	adjusted R^2
B	second factor or input variable investigated—speed in rpm
C	third factor or input variable investigated—amount of coolant in l/min
Cor. total	totals of all information corrected for the mean
CV	coefficient of variation
d.f.	degree of freedom
Prob. > F	proportion of time or probability you would expect to get the stated F value
PRESS	predicted residual error sum of squares
Pred. R^2	predicted R^2
R^2	coefficient of determination
S.D.	square root of the residual mean square

Greek symbol

α	angle of attack of the roller

The aim of the present study is to develop a surface roughness prediction model for flow-formed AA6061 tube. The factors investigated are the speed of the mandrel, the feed and the amount of coolant used. The surface roughness is the response investigated. The experimental plan is based on RSM's Box-Behnken design.

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 the axial flow 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.

2.2. *Equipment*

The present investigation was performed on a four-axis CNC flow-forming machine with a single roller. The flow-forming 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, Dc mm is given. The depth of cut is given by maintaining the gap between the mandrel and the roller less 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 excellent surface finish.

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 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.

2.4. *Forming conditions*

Preliminary tests were carried out to find out the factors that affect the surface roughness of a flow-formed tube. It was found that the depth of cut, the roller angle, the speed of the mandrel, the longitudinal feed given and the amount of coolant used had significant effect on the surface roughness. In this research work, multiple pass flow-forming has been done. The process parameters for tube production are entirely different from the process parameters for minimum surface roughness. Two type of lubricants namely MoS_2 and graphite were used in this research. Considerable difference in the plastic flow was felt between no lubricant condition and lubricant condition. However, the type of lubricant did not produce considerable difference in the plastic flow. Also, scratch marks were seen in the inside surface of the tube if no lubricant was used. But the surface roughness was the same irrespective of the lubricant used. The roller angles had significant effect on the surface roughness. Rollers with four different roller angles namely 60°, 45°, 30° and 20° were used in this research. Fig. 1 shows the tubes made from rollers of different angle of attack, α. A roller with $\alpha = 60°$ produced flange type error on the surface of the preform as shown in Fig. 1 (extreme right in Fig. 1). So, this roller was not used for further forming. A roller with $\alpha = 45°$ produced fish scale type surface defect (tube in the middle of Fig. 1). In the above two cases of forming, the preform due to large attack angle has tried to flow more in the radial direction that in the axial direction resulting in fish scales and flange type errors. However, the rollers with

Fig. 1 – Flow-formed tubes made from different rollers.

$\alpha = 30^\circ$ and $\alpha = 20^\circ$ produced excellent tubes. A surface finish of 2 μm was measured on the tube made with the roller having an angle of 20°. Roller with $\alpha = 30^\circ$ produced a surface finish of 1.4 μm.

An earlier research by the authors (Joseph Davidson, 2008) revealed that maximum deformation of the preform can be achieved at a depth of cut of 2 mm, mandrel speed of 250 rpm and a feed of 50 mm/min. However, the surface roughness at a depth of cut of 2 mm was in excess of 5 μm. Further research revealed that a different set of process parameter is needed for good surface finish. So, the tube was flow-formed to the required length using the parameters mentioned in (Joseph Davidson, 2008). Then the process parameters for surface finish were investigated by giving a depth of cut of 0.1 mm on the outer surface of the fully flown tube by varying the speed, the feed and the amount of coolant as dictated by the design matrix developed by RSM.

3. Design of experiments

Design of experiments is a powerful analysis tool analyzing the influence of process variables over some specific variable, which is an unknown function of these process variables. It is the process of planning the experiments so that appropriate data can be analyzed by statistical methods, resulting in valid and objective conclusions. Statistical approval to experimental design is necessary if we wish to draw meaningful conclusions from the data. (Montgomery, 1997).

4. Response surface methodology (RSM)

RSM is a collection of statistical and mathematical methods that are useful for modeling and analyzing engineering problems. In this technique, the main objective is to optimize the response surface that is influenced by various process parameters. RSM also quantifies the relationship between the controllable input parameters and the obtained response surfaces (Montgomery, 1997; Kwak, 2005). The design procedure of RSM is as follows (Noordin et al., 2004; Gunaraj and Murugan, 1999).

1. Designing a series of experiments for adequate and reliable measurements of the response of interest.
2. Developing a mathematical model of the response surface with the best fittings.
3. Finding the optimal set of experimental parameters that produce a maximum or minimum value of response.
4. Representing the direct and interactive effects of the process parameters through two- and three-dimensional plots.

5. Mathematical model of surface roughness

5.1. *Response equation for surface roughness*

RSM's Box-Behnken design consisting of 17 experiments was conducted for developing the mathematical model for surface roughness attained by the flow-formed tube. The input parameters and their levels chosen for this work are given in Table 1. The surface roughness results for the 17 experiments are given in Table 2.

Table 1 – Input parameters and their levels

S. no.	Parameter	Low level	High level
1	Feed (mm/min)	25	75
2	Speed (rpm)	250	350
3	Coolant (l/min)	1.2	3.6

Table 2 – Experimental layout for the Box-Behnken design

Run no.	Factors			Surface roughness, Ra (μm)
	Feed	Speed	Coolant	
1	50	300	2.4	1.90
2	25	300	3.6	1.49
3	50	300	2.4	1.90
4	75	300	3.6	4.45
5	50	250	3.6	2.37
6	25	300	1.2	1.40
7	50	300	2.4	1.90
8	50	350	1.2	2.10
9	75	350	2.4	4.60
10	50	350	3.6	2.31
11	50	250	1.2	1.48
12	75	300	1.2	3.28
13	25	250	2.4	2.64
14	75	250	2.4	4.43
15	25	350	2.4	2.01
16	50	300	2.4	1.90
17	50	300	2.4	1.90

Table 3 – Model summary statistics

Source	Standard deviation	R^2	Adj. R^2	Pred. R^2	PRESS	
Linear	0.72	0.6264	0.5402	0.3058	12.55	
2FI	0.79	0.6578	0.4524	−0.3929	25.18	
Quadratic	0.15	0.9912	0.9798	0.8587	02.56	Suggested

Table 4 – ANOVA table for response surface model (response: surface roughness, Ra (μm))

Source	Sum of squares	d.f.	Mean square	F-value	Prob > F	
Model	17.92	9	1.99	87.26	<0.0001	Significant
A-Feed	10.63	01	10.63	465.76	<0.0001	
B-Speed	1.250E − 003	01	1.250E − 003	0.055	0.8216	
C-Coolent	0.70	01	0.70	30.52	0.0009	
AB	0.16	01	0.16	7.01	0.0330	
AC	0.29	01	0.29	12.78	0.0090	
BC	0.12	01	0.12	5.07	0.0591	
A^2	4.69	01	4.69	205.42	<0.0001	
B^2	0.91	01	0.91	39.91	0.0004	
C^2	0.38	01	0.38	16.61	0.0047	
Residual	0.16	07				
Cor Total	18.08	16				

The response equation for surface roughness (Ra) so obtained is given by

$$\begin{aligned}\text{Surface roughness} = {} & +20.13 - 0.19230 \times \text{Feed} - 0.11255 \\ & \times \text{Speed} + 1.64583 \times \text{Coolent} + 1.60000\text{E} \\ & - 004 \times \text{Feed} \times \text{Speed} + 9.00000\text{E} - 003 \\ & \times \text{Feed} \times \text{Coolent} - 2.83333\text{E} - 003 \\ & \times \text{Speed} \times \text{Coolent} + 1.68800\text{E} - 003 \\ & \times \text{Feed}^2 + 1.86000\text{E} - 004 \times \text{Speed}^2 \\ & - 0.20833 \times \text{Coolent}^2 \end{aligned} \quad (1)$$

6. Results and discussion

6.1. *ANOVA and response surface graphs*

The analysis of variance (ANOVA) was applied to study the effect of the input parameters on the surface roughness. Table 3 gives the model summary statistics. It reveals that quadratic model is the best suggested model. So, for further analysis this model was used. Table 4 gives the ANOVA for the response surface model for the surface roughness. ANOVA is commonly used to summarise the test for significance on individual model co-efficients. The value of "Prob > *F*" for model is less than 0.0500 which indicates that the model terms are significant, which is desirable as it indicates that the terms in the model have a significant effect on the response. The Model *F*-value of 87.26 implies that the model is significant. There is only a 0.01% chance that a "Model *F*-value" this large could occur due to noise.

Table 5 gives the regression statistics. The co-efficient of determination R^2 is used to decide whether a regression model is appropriate. The co-efficient of determination R^2 provides an exact match if it is 1 and if the residual increases R^2 decreases in the range from 1 to 0. As the number of variables increases, the residual decreases, so that the co-efficient of determination R^2, increases its value. So, to obtain a more precise regression model judgment, co-efficient of determination R^2 adjusted for the degrees of freedom Adj. R^2 is used. Adj. R^2 is used for comparing the residual per unit degree of freedom. Adequate precision compares the range of the predicted values at the design points to the average prediction error. It is a measure of the signal to noise ratio. Ratio greater than 4 indicates adequate model discrimination. In this particular case, it is 28.551, which is well above 4. So the model can be used to navigate the response space. Further, it is seen that the R^2 value is 0.9912 and the Adj. R^2 is 0.9798. The predicted R^2 value of 0.8587 is in reasonable agreement with the Adj. R^2 value. The R^2 value in this case is high and close to 1, which is desirable.

The adequacy of the model has also been investigated by the examination of residuals (Montgomery, 1997). The residuals, which are the difference between the respective observed responses and the predicted responses, are examined using

Table 5 – Regression statistics

Standard deviation	0.15
Mean	2.47
CV	6.10
PRESS	2.56
R^2	0.9912
Adj. R^2	0.9798
Pred. R^2	0.8587
Adeq precision	28.551

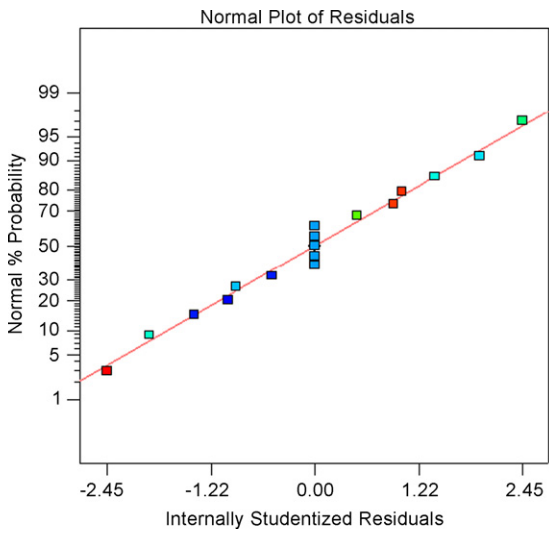

Fig. 2 – Normal probability plot of residuals for surface roughness data.

the normal probability plots of the residuals and the plot of the residuals versus the predicted response. If the model is adequate, the points on the normal probability plots of the residuals should form a straight line. On the other hand, the plots of the residuals versus the predicted response should be structure less, that is, they should contain no obvious pattern (Noordin et al., 2004). The normal probability plots of the residuals and the plots of the residuals versus the predicted responses for the surface roughness values are shown in Figs. 2 and 3. It revealed that the residuals generally fall on a straight line implying that the errors are distributed normally. Also Fig. 3 revealed that they have no obvious pattern and unusual structure. This implies that the model proposed is adequate and there is no reason to suspect any violation of the independence or constant variance assumptions (Noordin et al., 2004). Figs. 3–5 gives the 3D surface graphs for the surface

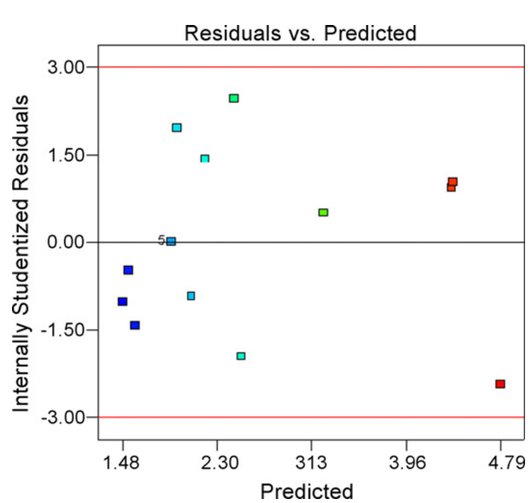

Fig. 3 – Plot of residuals vs. predicted surface roughness values.

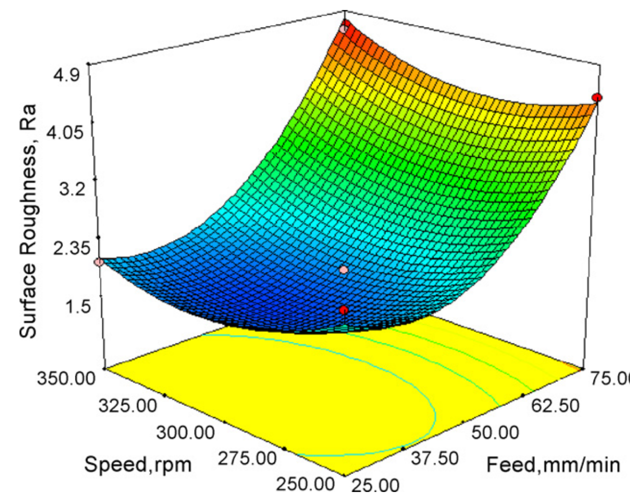

Fig. 4 – 3D surface graph for the surface roughness at coolant = 2.4 l/min, as speed and feed varies.

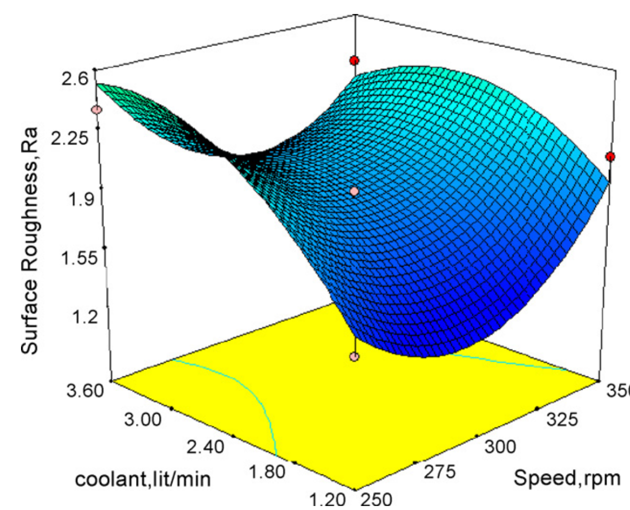

Fig. 5 – 3D surface graph for the surface roughness at feed = 50 mm/min as speed and coolant varies.

roughness. As the model is adequate these 3D surface plots can be used for estimating the surface roughness values for any suitable combination of the input parameters namely the speed of the mandrel, the longitudinal feed and the amount of coolant.

Eq. (1) gives the prediction model for surface roughness in terms of actual factors. It reveals that surface roughness increases with increase in feed and coolant. Surface finish improved with increase in speed of the mandrel. However, since flow-forming is a high energy process involving high axial and radial forces, beyond 300 rpm the surface finish deteriorated due to vibration of the flow-forming apparatus.

The 3D surface graphs for the surface roughness are shown in Figs. 4–6. It is clear from Fig. 4 that surface roughness increases with increase in feed rate. A slow feed rate uniforms the outer surface thus increasing the surface finish. Good surface finish is obtained for a speed of 300 rpm. Large speed

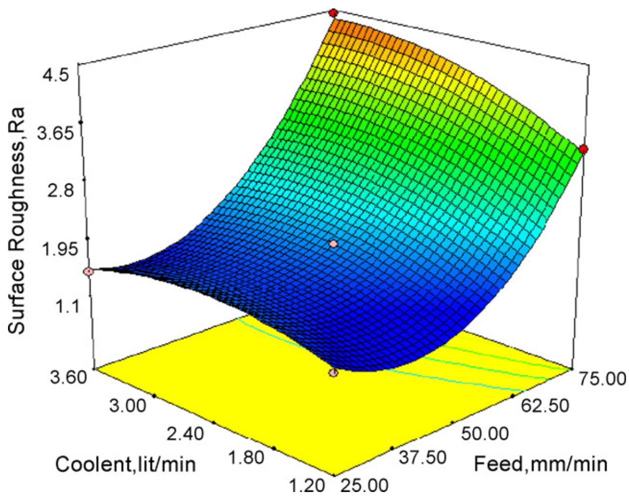

Fig. 6 – 3D surface graph for the surface roughness at speed = 300 rpm as coolant and feed varies.

Table 6 – Sample predicted data from the RSM model

Speed	300
Feed	30
Coolant	2
Surface roughness, Ra (μm)	
Experimental	1.70
RSM predicted	1.59
Error (%)	6.4

combined with large feed produce excessive adiabatic heating in the preform leading to bad surface finish.

Fig. 5 gives the 3D surface graph for surface roughness at feed = 50 mm/min as speed and coolant varies. The presence of coolant decreases the surface finish. However, complete absence of coolant produced flakes on the surface resulting in bad surface finish. Hence, a minimum amount of coolant equivalent to level 1 is required for good surface finish. The coolant was used to remove the heat generated during the forming process to avoid excessive adiabatic heating.

Fig. 6 gives the 3D surface graph for the surface roughness at speed = 300 rpm as coolant and feed varies. Higher feed and higher coolant levels destroyed the surface finish achievable.

7. Confirmation test

In order to verify the accuracy of the model developed, confirmation experiment was performed (Table 6). The test condition for the confirmation test was so chosen that they be within the range of the levels defined previously. The predicted value and the associated experimental value were compared and the percentage error was calculated. The error percentage is within permissible limits. So the response equation for the surface roughness evolved through RSM can be used to successfully predict the surface roughness values for any combination of the feed, speed and the coolant values within the range of the experimentation conducted.

8. Conclusion

In this paper, RSM has been used to determine the surface roughness attained by the flow-formed tubes for various input parameters namely the feed, speed and the coolant. A RSM model can successfully relate the above process parameters with the response, surface roughness. The verifying experiment has shown that the predicted value agrees with the experimental evidence.

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