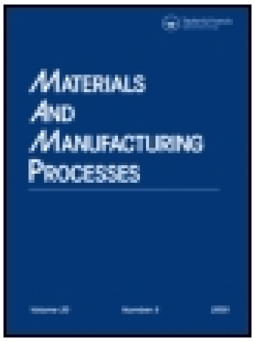

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Modeling of Aging Treatment of Flow-Formed AA6061 Tube

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Flow-forming is a chipless metal forming process which employs an incremental rotary point deformation technique. An annealed AA6061 aluminum tubing preform was cold flow-formed into a seamless tube. A multiple pass flow-forming was performed. The strength of the flow-formed tube was altered by performing artificial aging treatment. The present research investigates the possibility of using response surface methodology (RSM) for predicting the hardness of the artificially aged flow-formed tube. Experiments were performed to investigate the effect of aging process parameters like solution time (ST), aging time (AT) and aging temperature (ATEMP) on the hardness of the flow-formed tube after artificial aging treatment. Experimental plan is performed by a standard RSM design called Box–Behnken Design. The results of analysis of variance (ANOVA) indicate that the proposed regression model obtained can adequately predict hardness values within the limits of the factors being studied.

Keywords AA6061 alloy; Aging treatment; Box–Behnken design; Flow-forming; Hardness; Mg_2Si; Optical micrographs; Prediction; Precipitation hardening; Response equation; RSM.

1. Introduction

Flow-forming is a cold-forming rotary point extrusion process [1]. In the 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. Rajan et al. investigated the effect of heat treatment of preform on the mechanical properties of flow-formed AISI steel tubes [1]. Chang et al. successfully fabricated 2024 aluminum tube by flow-forming through a thermomechanical treatment process [2]. Lee et al. studied the mechanical properties of polypropylene pipes formed by multiple pass flow-forming process [3]. Flow-forming offers excellent dimensional tolerances, and it improves the mechanical properties of the product considerably. The mechanical properties can be further enhanced by artificial aging treatment [4–6]. Liu et al. used neural network and genetic algorithm to optimize the aging treatment in lead frame copper alloy [7]. Sun et al. studied the effect of plastic deformation on the aging behavior of aluminum alloy [8]. It has been reported that intermediate plastic deformation increases aging rate by providing homogenously distributed nucleation sites for precipitates in the matrix [8–10]. Lee et al. [11] have studied the effect of aging treatment on the mechanical properties of flow formed C-250 maraging steel tubes.

Recently, researchers have successfully demonstrated the application of statistical and artificial intelligence techniques in the modeling and optimization of process parameters of various manufacturing processes. Saigal et al. used Taguchi technique to optimize the heat treatment process of alumina/aluminum metal matrix composites [12].

Joseph Davidson et al. used response surface methodology to model the process parameters of EDM process [13]. Selvakumar et al. used neural network to predict the densification behavior of sintered aluminum preforms [14]. There is a great need to simulate the aging treatment process by statistical methods to reduce the time and money involved in the expensive and time-consuming conventional experimental methods. In this investigation, response surface methodology (RSM) has been used to predict the hardness of flow-formed and aged AA6061 tubes. Three aging treatment process parameters, namely, the solution treatment time (ST), the aging time (AT), and the aging temperature (ATEMP) have been used as input parameters to predict the desired output parameter, namely, the hardness, HV of the flow-formed tube.

2. Experimental work

The AA6061 tube used in the present investigation was cold flow-formed on a 4 axis CNC flow-forming machine (Fig. 1) with a single roller [15]. Figure 2 shows a fully flown tube of AA6061 alloy. 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, 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 minimum or no surface damage [16].

2.1. 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

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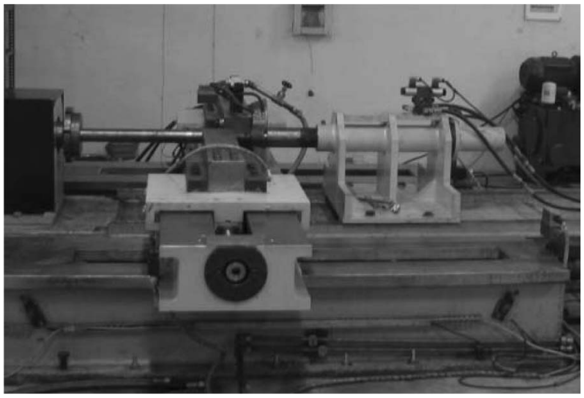

FIGURE 1.—Flow-forming set up used in this work.

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.

2.2. Aging Treatment

The flow-formed tube was cut into small pieces for aging treatment. The samples were solution treated at 530°C for various solution treatment times as dictated by the experimental run matrix given in Table 2. The samples were quenched in water after solution treatment. The solution treated samples were then aged at different time and temperatures. The optical micrograph of the flow-formed tube in the as flow formed condition is shown in Fig 3. Figure 4 gives the optical micrograph of the aged flow-formed sample. The hardness was then measured on a SHIMADSU HSV20 hardness testing machine under a load of 1000 g and held for 10 s.

FIGURE 2.—Flow-formed AA6061 tube.

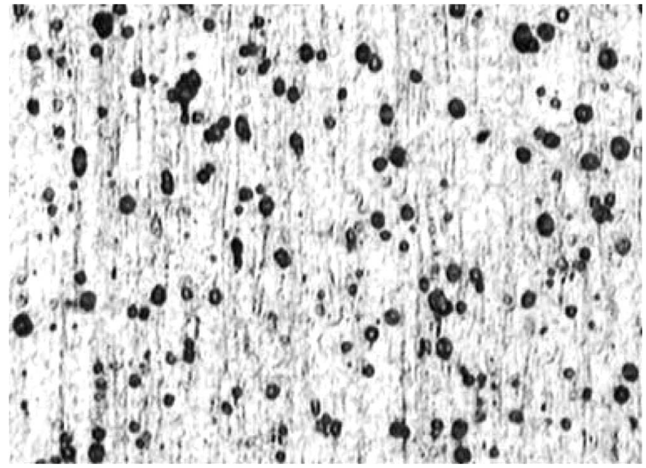

FIGURE 3.—Optimal micrograph of flow-formed tube in the longitudinal direction.

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 [17]. In this work response surface methodology has been used to model the process.

4. MATHEMATICAL MODEL OF HARDNESS

4.1. Response Equation for Hardness

RSM's Box–Behnken design consisting of 17 experiments was conducted for developing the regression model for hardness attained by the flow-formed tube after artificial aging. The input parameters and their levels chosen for this

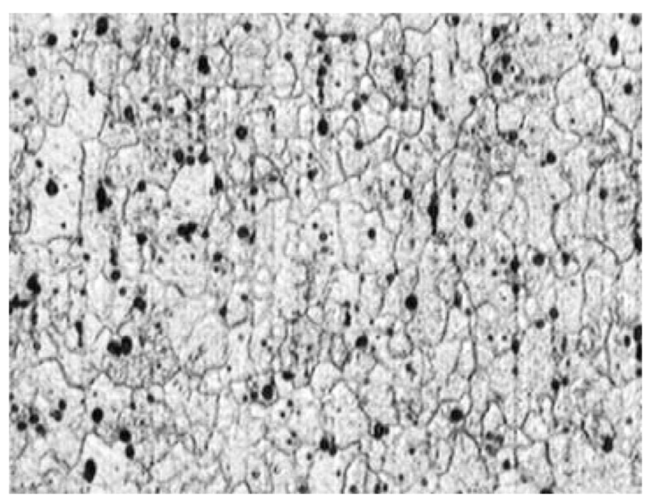

FIGURE 4.—Optical micrograph of the aged flow-formed tube in the longitudinal direction.

Table 1.—Input parameters and their levels.

S. No	Parameter	Unit	Low Level	High Level
1	Solution Time (ST)	Hour	2	6
2	Aging Time (AT)	Hour	3	9
3	Aging Temperature (ATEMP)	Celsius	130	200

Table 3.—Model summary statistics.

Source	Std. Dev	R^2	PRESS	
Linear	10.16	0.5213	2576.19	
2FI	10.60	0.5993	4804.97	
Quadratic	06.20	0.9041	4300.00	Suggested

work are given in Table 1. The hardness results for the 17 experiments are given in Table 2.

The response equation for hardness (HV) so obtained is given by

$$\begin{aligned}\text{Hardness} = &+105.27296 + 21.55357 * \text{ST} + 6.70833 * \\ &\text{AT} - 1.00255 * \text{ATEMP} - 0.12500 * \text{ST} * \\ &\text{AT} - 0.032143 * \text{ST} * \text{ATEMP} \\ &+ 0.066667 * \text{AT} * \text{ATEMP} - 1.81250 * \\ &\text{ST}^2 - 1.27778 * \text{AT}^2 + 3.26531\text{E} - 003 * \\ &\text{ATEMP}^2.\end{aligned}$$

5. Results and discussion

5.1. ANOVA and Response Surface Graphs

The analysis of variance (ANOVA) was applied to study the effect of the input parameters on the hardness. 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 hardness. 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. A value less than 0.05 for "Prob > F" indicates that the terms in the model have a significant effect on the response. The Model F-value of 7.33 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. 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 9.338, 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 0.9041. The R^2 value in this case is high and close to 1, which is desirable.

Figures 3–5 give the 3D surface graphs for the hardness. As the model is adequate these 3D surface plots can be used for estimating the hardness values for any suitable combination of the input parameters namely the solution time, the aging time, and the aging temperature.

Table 6 reveals that RSM can be used for predicting the hardness of the aged flow-formed tube successfully. Figure 5 shows the effects of solution treatment time and artificial aging time on the hardness for an aging temperature of 200°C. It can be seen that initially the hardness values increase with solution treatment time up to 4 hours and thereafter no definite change is observed. The reason for increase in the hardness values with solution treatment time is due to the higher dissolution rate of Mg_2Si in aluminium. The hardness reaches a maximum value at a solution time of around 4 hours and then it decreases. The peak hardness is attained at an aging time of around 7 hours.

Figure 6 shows the effects of solution treatment time and artificial aging temperature on the hardness for an aging time

Table 2.—Experimental layout for the Box–Behnken design.

Run No.	Factors ST	AT	ATEMP	Hardness, HV
1	4	6	165	122
2	6	6	130	105
3	4	9	200	141
4	4	6	165	122
5	6	3	165	108
6	2	6	200	137
7	6	6	200	126
8	2	6	130	107
9	4	9	130	104
10	4	6	165	122
11	4	3	200	111
12	4	6	165	122
13	4	3	130	102
14	2	3	165	92
15	4	6	165	122
16	6	9	165	113
17	2	9	165	100

Table 4.—ANOVA table for response surface model (response: hardness (HV)).

Source	Sum of Squares	DF	Mean Square	F Value	Prob	
Model	2534.19	9	281.58	7.33	0.0078	significant
A (ST)	32.00	01	32.00	0.83	0.3916	
B (AT)	253.13	01	253.13	6.59	0.0371	significant
C (ATEMP)	1176.13	01	1176.13	30.63	0.0009	significant
AB	2.25	01	2.25	0.059	0.8157	
AC	20.25	01	20.25	0.53	0.4912	
BC	196.00	01	196.00	5.11	0.0584	
A^2	221.32	01	221.32	5.76	0.0474	significant
B^2	556.84	01	556.84	14.50	0.0066	significant
C^2	67.37	01	67.37	1.75	0.2269	
Residual	268.75	07				
Cor Total	2802.94	16				

TABLE 5.—Regression statistics.

Std. Dev.	6.20	R^2	0.9041
Mean	115.06	PRESS	4300
C.V.	5.39	Adeq. Precision	9.3380

of 7 hours. A steep increase in hardness is felt between the temperatures 165°C and 200°C. A peak hardness of 141 HV was attained at a solution time of 4 hours. The hardness increased rapidly with the aging temperature. This is due to the accelerated precipitation of Mg_2Si from the Al matrix.

Figure 7 shows the effects of the aging time and the aging temperature on the hardness for a solution time of 4 hours. Peak hardness was achieved at an aging time of 7 hours. A steep increase in hardness is experienced between 3 to 7 hours. The solubility of Mg and Si in the Al matrix increases with increase in the solution treatment time. During the precipitation hardening process, Mg_2 Si will be precipitated out from the supersaturated solid solution of Al and the other alloying elements like Mg, Si, Cu, etc. This precipitation will increase with increase in the aging time, attributing to its increase in hardness.

6. CONFIRMATION TEST

In order to verify the accuracy of the model developed, confirmation experiments were performed (Table 6). The test condition for the confirmation tests were 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.

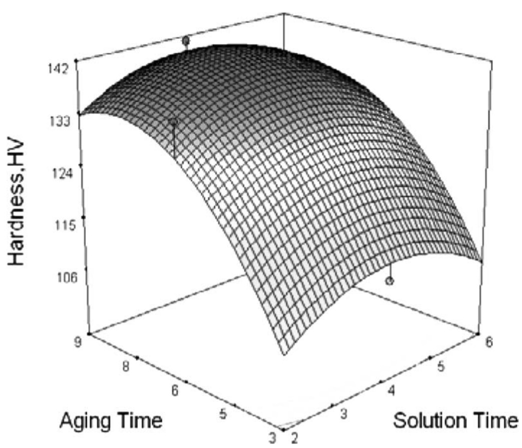

FIGURE 5.—3D surface graph for the hardness at Aging Temperature = 200°C, as Aging Time and Solution Time varies.

TABLE 6.—Sample predicted data from the RSM model.

			Hardness (HV)		
ST	AT	ATEMP	Experimental	RSM predicted	Error %
2	4	170	107	104	2.8

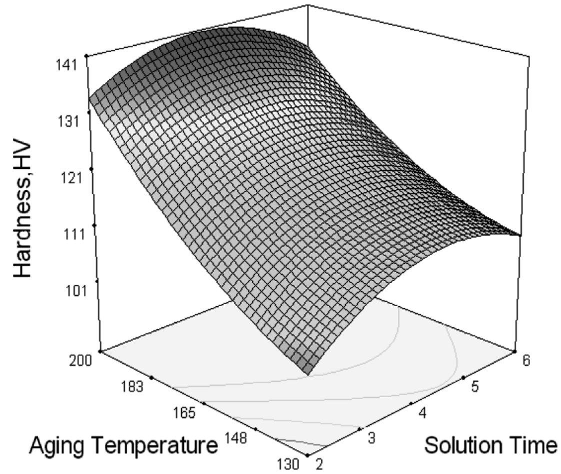

FIGURE 6.—3D surface graph for the hardness at Aging Time = 7 hours as Aging Temperature and Solution Time varies.

The error percentage is within permissible limits. So the response equation for the hardness evolved through RSM can be used to successfully predict the hardness values for any combination of the solution time, the aging time and the aging temperature values within the range of the experimentation conducted.

7. CONCLUSION

In this article, the aging behavior of AA6061 flow-formed tubes has been modeled using response surface methodology. RSM has been used to determine the hardness attained by the flow-formed tubes for various input parameters, namely, the solution time (ST), the aging time (AT), and the aging temperature (ATEMP). A RSM model can successfully relate the above aging process parameters with the response, hardness. The verifying experiment has shown that the predicted value agrees with the experimental evidence.

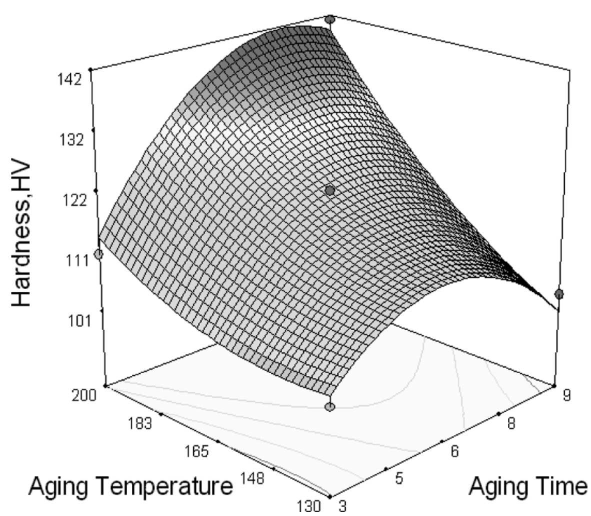

FIGURE 7.—3D surface graph for the hardness at Solution Time = 4 hours as Aging Temperature and Aging Time varies.

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