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PROCESS PARAMETERS OPTIMIZATION ON PORTHOLE-DIE HOT EXTRUSION OF ALUMINIUM ALLOY TUBES USING TAGUCHI METHOD

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ABSTRACT

During the hot extrusion process of aluminum alloy 6061, the process parameters significantly affect the mechanical properties of extruded products. For better extruded components, these process parameters need to be optimized. An experimental investigation and analysis has been carried out to optimize the billet temperature, mandrel length, convex die angle and tooling temperature on porthole-die hot extruded Aluminium alloy 6061 tubes under extrusion ratio of 24.03. During the experiments the above parameters were varied and Taguchi's optimization approach was applied to obtain an optimal setting of parameters. From the experimental results and further analysis, it is concluded that under 95% confidence interval the minimum extrusion load could be obtained with the billet temperature 420°C, mandrel length 8mm, convex die angle 105° i.e.(A_3, B_2, C_3). And the highest tensile strength was obtained with billet temperature 410°C, mandrel length 11mm, tooling temperature 400°C i.e. (A_2, B_3, D_1). However, the most significant process parameters responsible for minimum extrusion load and maximum tensile strength with their percent contribution were convex die angle 97.83% and mandrel length 81.16% respectively.

Keywords: Porthole-die, hot extrusion tube, aluminium alloy 6061, mechanical properties, Taguchi method, orthogonal array**.**

1. INTRODUCTION

Aluminium alloys, Al 6061 are some of the most widely used materials today which spans the entire range of industries. Due to a low thermal expansion coefficient, high strength to weight ratio, high wear and corrosion resistance this alloy is commonly used in the aerospace and automobile industries. Because of the widespread use of this alloy, it is important to understand their mechanical property and machinability. The port-hole extrusion process, which is, also called the welding chamber method, is broadly utilized to produce tubes and hollow sections (Jo et al., 2003). Porthole-die extrusion has a great advantage in the forming of hollow section products, which are difficult to produce by conventional extrusion. A product of hollow section can be extruded using special dies based on a welding chamber with a spider die, a porthole-die, a bridge die, etc. The billet in the container flows through the porthole and welds by high pressure in the welding chamber. Many researchers have experimented before 1970s to explore the mechanical properties of this alloy and this paper focuses on porthole-die hot extrusion process. The single-hole extrusion process is commonly adopted in industry to produce circular tubes. The multi-hole extrusion process has greater productivity with an efficient extrusion tooling design. Most multi-hole extrusion processes are applied to produce seemed-hole hollow section tubes using the porthole-die in which the divided bars are welded in the welding chamber before being extruded to the exit (Lee et al., 2005). In the multi-hole extrusion, most research efforts were focused to search for an optimum die design to achieve a balanced flow at the die exit to avoid any bending of extruded tubes. Analytical approach such as upper-bound method has been applied by many researchers to study, the effect of the process variables of the extrusion pressure and extruded product's shape (Ulysse and Johnson, 1998). An investigation on the improvement of welding strength in three-dimensional porthole-die extrusion tubes, reported an increased welding pressure for an increased height of the chamber (Kim et al., 2002). They concluded that the welding pressure in the chamber of the modified porthole-die is higher than that of the conventional porthole-die. A study on the influence of process parameters on hot extrusion of magnesium alloy tubes reported that the billet heating temperature, the initial extrusion speed and the container temperature would affect the mechanical properties of extruded products (Hsiang and Lin, 2007). Another investigation determined the welding pressure in the non-steady-state porthole-die extrusion of improved Al7003 hollow section tubes and concluded that the welding strength is affected by many parameters, such as extrusion ratio, extrusion speed, die's shape, bearing length, billet temperature and container temperature (Jo et al., 2006). In porthole extrusion, the welding pressure that was developed between neighboring streams determines the strength of the tube. The welding strength is affected by many parameters, such as extrusion ratio, extrusion speed, die's shape, bearing length, billet and container temperature, etc. (Lee et al., 2005; Ulysse & Johnson, 1998; Kim et al., 2002; Hsiang & Lin, 2007; Jo et al., 2006). The objective of the present study is to analyze the behavior of metal flow and to optimize the process parameters such as billet temperatures, bearing lengths (mandrel length), convex die angle and container temperature (tooling temperature) to yield good mechanical properties (Saidur et al. 2008). Several of the process parameters involved are the extrusion temperature, the extrusion speed, the friction, the extrusion reduction ratio, and the eccentricity of holes. It is then necessary to build up the relations of the interactive influence among these process parameters to design effective dies. During continuous extrusion, the mandrel that is chosen to balance the material flow causes material wastage and defective tubes. The flow has also been controlled by varying the cone angle which reduces the friction and adding of dead metal zone over the die that improves life of the die by reducing the extrude pressure. Taguchi's technique has been popular for parameter optimization in design of experiments (DOE) for decades (Lee, 2000; Ross, 1998; Sahin et al., 2005; Yakut at al., 2006; Ganapathy et al., 2009). The effects of process parameters involved in the hot extrusion process were investigated by researchers using the finite element analysis as well (Lee et al., 2002; Lee and Im, 2002; Peng and Sheppard, 2004; Li et al., 2004; Hasanuzzaman et al, 2007). Another study investigated the effect of extrusion processing parameters, including the temperature, extrusion ratio, and structure of the extrusion die on microstructure and mechanical properties of as-extruded AZ31 sheets. It was concluded that applying the porthole die for the extrusion of the AZ31 sheet can make the grains fine and uniform, increase the mechanical properties and improve the anisotropy of the mechanical properties. When the annealing temperature is 300ºC, the as-extruded AZ31 sheet by the porthole die can obtain better mechanical properties and anisotropy (Jiang et al., 2008).

For the present work, Taguchi design of experiments were employed to study and analyze the effects of the process parameter on the multi-hole extrusion of aluminum alloy Al 6061 by the forward extrusion process using four channel die. This die is used to carry out hot extrusion using aluminum alloy billets 6061, which is extruded into form a tube of 2 mm thickness. The process parameters of hot extrusion are optimized with 3 channels die for optimum extrusion force (load) and tensile strength. Analysis of variance (ANOVA) is also carried out in order to find out the significant factors and their contribution to the response parameter. Finally the effects of the billet heating temperature, container temperature, convex die angle, bearing length on the mechanical properties such has tensile strength have been investigated and reported.

2. EXPERIMENTATION

An experimental program of forward hot extrusion was under taken in the present investigation. The aim of the present work is to study the effect of geometrical variables such as convex die angle and mandrel length and process parameters such as billet temperature and tooling temperature on the extrusion force and tensile strength. Experiments were conducted using Al 6061 as billet material. The material was cast and pre-extruded into a rod with a diameter of 50 mm and the rod was subsequently used as a billet for further extrusion into a circular hollow profile with an outside diameter of 40 mm and wall thickness of 2 mm. Each billet had a length of 70 mm. The extrusion tooling comprised of ram, container, die (with convex angle and split webs), mandrel, and welding chamber was made of the EN31 tool steel. The container has diameter of 60 mm and thereby a clearance of 5 mm was left for easy loading of the pre-heated billet into the container. Because of this clearance, upsetting took place prior to extrusion to fill the container completely. In order to study the influence of metal flow and therefore on weldability of metal and final microstructure, the die with three convex angles were introduced. Since the use of convex die angle allow an advantage change in the metal flow made within the deformation zone resulting in the imposing metal flow in the radial directions towards the die opening. This flow pattern allows higher extrusion exit speed, influences the extrusion pressure and results in a fine final microstructure, because of the change in the deformation route for the extruded metal. The geometrical features of the die land are a critical feature in obtaining defect free extruded parts. As the die land length (mandrel length) directly influences the amount of friction at the die-billet interface extrusion, die designers use this geometrical parameter to control the metal flow from the die. Appropriate die land geometrical features will allow uniform distribution of residual stresses in the extrude part as it emerges from the die. In the present investigation, mandrel length of 5, 8 and 11mm were chosen. The magnitude of the extrusion force was determined experimentally by means of force transducer. The tooling temperature was set at 10˚C lower than that of the billet temperature in order to allow part of the heat generated during extrusion to dissipate into the tooling. Extrusion ratio was kept at 24.03 and ram speeds were set at 2 mm/s. The processing of hot extrusion of Al 6061 alloy tubes using porthole-die is illustrated in Fig. 1 and the composition of Al 6061 alloy is given in Table 1. The tube tensile test, as specified by CNS 2111 and CNS 2112, was used for reference. A 200mm trial piece was cut from the tube. It was fixed between the two jaws of a tensile testing machine that weighs 30 tones. The gauge length of the tube taken for testing was L=100 mm. The welded zone was placed at the position of the tensile direction. Figure 2 shows a failure of test piece during the tensile test, at the tensile speed of 16.5 mm/min. When the gauge length is of L=106.38 mm, the wall of the longitudinal tube is observed to identify any breaking or cracking. The percentage elongation is 6.38%. All the experiments were repeated twice and recorded.

Table 1 Composition of aluminum alloy 6061

Composition (% wt)								
Al	Zn	Si	Fe	Mn	Cu	Cr	Mg	Ti
97.70	0.10	0.65	0.23	0.03	0.22	0.22	0.84	0.01

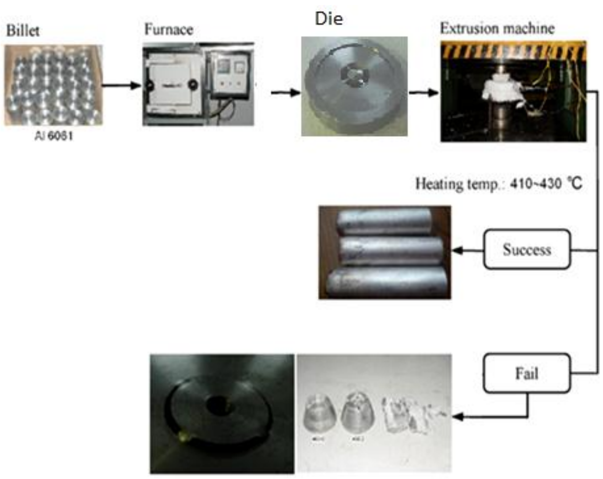

Figure 1 Processing of hot extrusion of Al 6061 alloy tubes using porthole-die

The ductility of the tube from the porthole die is tested by flattening test. Test specimens are obtained from the middle and rear parts of the initial long tube. The flattening test is conducted as shown in Fig. 3(a) with reference to the relevant specifications.

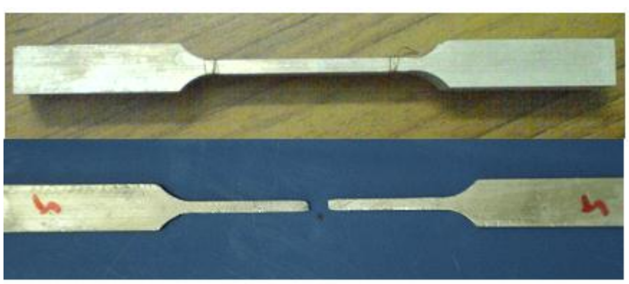

Figure 2 Failure of test piece during tensile test

The distance between the two plates is kept at 30 mm and the wall of the tube is examined for any defects (breaking or cracking). No defect was observed at this height as shown in Fig. 3(b). The flattening test was continued by increasing the load and it was observed that within the range of load (2.963-3.542 kN) the breaking of the tube occurred. This can be seen in Fig. 3(c).

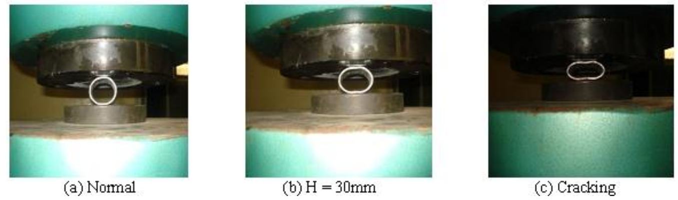

Figure 3 Flattening test

3. TAGUCHI APPROACH FOR PROCESS PARAMETERS OPTIMIZATION

In general experiments can be carried out in four ways: (1) trial and error, (2) one-factor-at-a-time experiments, (3) full-factorial experiments and (4) Taguchi's orthogonal arrays (OA). Orthogonal arrays can eliminate the bias produced by one-factor at a time experiments, and improve the experimental efficiency of full-factorial experiments. Based on the principle of maintaining the accuracy of experiment results, the use of orthogonal arrays, can considerably reduce the time required to perform the experiments, due to non-availability of press, difficult to conduct an experiment due to the high temperature and pressure inherent in hot extrusion. Further, die design using trial and error experiment in production presses is extremely expensive owing to the high cost of die manufacturing and lost production and increases the reproducibility of the experiment results.

In the present work the Design of Experiments procedure using Taguchi approach is implemented to study the effects of process parameters on the hot extruded Al alloy tubes by using porthole-die with four channels. In the present scenario of hot extrusion research, selection of optimum process parameters is highly essential to achieve the highest possible strength with lowest extrusion force (load). The optimum combinations of process parameters (control factors) that will give maximum tensile strength and minimum extrusion force (load) can be determined by following the Taguchi's approach. The process is said to be consistent if it is insensitive to the influence of the uncontrollable factors and this can be achieved by carrying out the trial conditions under the influence of noise factors. Taguchi suggested the use of orthogonal arrays, which are the shortest possible matrix of permutations and combinations of the controlling parameters. The main aim of this method is that when all the parameters are varied at the same time their effects on the response parameters can be studied simultaneously. The orthogonal array is selected based on the number of degrees of freedom, which is determined from the number of factors, number of selected interactions, and the number of levels of each factor. Once the appropriate OA has been selected, the main factors and interactions, if any, can be assigned to the various columns. After setting the test strategy the test runs are performed in random order. Finally the test results are analyzed using signal to noise ratio to determine the optimum process parameters and influence of individual factors at the optimum condition.

3.1 Selection of control factors

The objective of the present work is to identify the optimal process parameter settings which would optimize the load and tensile strength of hot extruded tubes. The process parameters generally considered for hot extrusion process of Al 6061 alloy tubes using porthole-die method include extrusion speed, die shape, billet temperature, mandrel length, convex angle, tooling temperature, extrusion ratio, port hole number and mandrel shape, etc. In Taguchi method, the selection of influential parameters for analysis is a critical issue. For the present case, the most influential process parameters for the analysis are selected based on studies reported in literature (Lee et al., 2005; Ulysse & Johnson, 1998; Hsiang & Lin, 2007; Lee & Im, 2002) with main focus on tensile strength and extrusion force (load) and they are listed in Table 2. These four input parameters are taken as control factors and each factor has been considered with three levels as shown in Table 2.

Table 2 Control parameters and levels

Sl. No.	Control factor	Label	Level 1	Level 2	Level 3
1	Billet temperature (°C)	A	400	410	420
2	Mandrel length (mm)	B	5	8	11
3	Convex angle (°)	C	45	75	105
4	Tooling temperature (°C)	D	400	405	410

Since the number of degrees of freedom is 8, an orthogonal array (inner array) L_9 has been found suitable for the present design. The measurements of response parameters vide: load and tensile strength have been repeated twice and the variation occurred due to noise has been listed in the outer array. Table 3 shows the experimental layout with assignments of columns to the main factors and the noise factors.

3.2 Signal-to-noise ratio

The control factors that may contribute to decreased deviation (improved quality or performance) can be quickly identified by looking at the amount of variations present as a response. Though the analyses of the test results addressed the factors which might affect the average response, yet there is interest in the effect on variation as well. Taguchi has created a transformation of the repetition data to another value which is a measure of the variation present. The transformation is the signal to noise ratio (SNR). The SNR consolidates several repetitions (at least two data points are required) into one value which reflects the amount of variations present. There are different SNR available depending on the type of characteristic, such as Lower-the-better (LTB), nominal-the-best (NTB), or higher-the-better (HTB). In the present work lower-the-better and higher-the-better (HTB) quality characteristics have been used for load and tensile strength respectively. The SNR values are computed by using the following equations (1) and (2) respectively for HTB and LTB quality characteristics.

Table 3 Taguchi's Experimental Test Layout (L_9 OA)

Run	L9 OA (Inner array) (Control factors)				L2 OA (Outer array)			
					Load (kN)		Tensile strength (kN/mm2)	
	A	B	C	D	1	2	1	2
1	1	1	1	1	844.95	845.05	292.74	292.84
2	1	2	2	2	751.95	752	302.17	302.27
3	2	3	1	2	829	829.05	341.46	341.56
4	2	2	3	1	546.05	545.95	336.75	336.85
5	2	1	2	3	729	729.05	300.12	300.22
6	3	3	2	1	717.95	717.95	346.85	346.95
7	3	1	3	2	562.05	561.95	293.46	293.56
8	1	3	3	3	579.05	579.05	334.75	334.85
9	3	2	1	3	797	796.95	325.39	325.49

Table 4 SNR table

Run	SNR (load)	SNR (tensile strength)
1	-58.5371	49.3311
2	-57.5241	49.6065
3	-58.3714	50.6681
4	-54.7439	50.5474
5	-57.2548	49.5473
6	-57.1219	50.8041
7	-54.9947	49.3525
8	-55.2543	50.4957
9	-58.0289	50.2494

$$SNR = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^{\,2}}\right] \qquad (1)$$

$$SNR = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}y_i^{\,2}\right] \qquad (2)$$

where n is the number of levels of indicative factor (noise factor), in the present work it is equal to the number of repetitions at each trial run condition and y_i is the response variable, in the present work it is the load and tensile strength from the measurements.

4. RESULTS AND DISCUSSION

Experiments were undertaken according to the trial run conditions designed by Taguchi's OA (L_9) as shown in Table 3. The extrusion force (load) and tensile strength are considered as the response variables while computing the signal to noise ratio in the optimization procedure and hence the extrusion force and tensile strength are measured twice and recorded for each trial run. The results are then analyzed by means of the Taguchi's signal to noise ratio (SNR) for maximizing the tensile strength and minimizing extrusion force (responses) while minimizing the noise effects. Using Eq. (1&2) the SNR values were computed for all the 9 trial run conditions and the values are tabulated in Table 4. The control factors and their significant effects on the response parameters were also verified by analysis of variance (ANOVA), which is performed separately for the individual response variables. These are illustrated in the following section.

4.1 Extrusion force (Load)

Analysis of variance, ANOVA was carried out based on signal to noise ratio data from Table 4 in order to determine the significance of the control factors on extrusion force and tensile strength. The average SNR values at low, medium and high levels for each response are illustrated in Table 5.
In the present investigation ANOVA is used to determine the significance of control factors and also to find out percentage contribution of the factors to the total variation of responses.

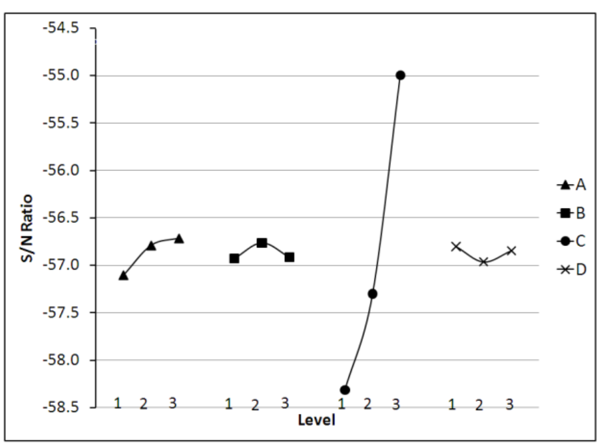

Figure 4 Main effects of control factors on Extrusion load

The main effects of the control factors on extrusion force (load) in terms of SNR are shown in Fig. 4. The average effect of each parameter on the response variables based on SNR can be seen from this figure, when the control parameters change from one level to another. It is clear from the Fig. 4 that process parameter convex angle (C) has more strong effect on extrusion force (load) than the rest of the parameters. The sequence of parameters in the order of significant effects are C, A, and B. Levels A_3, B_2, C_3 and D_1 appear to be the best choice in terms of mean response and variation. From Table 5 it is clear that the SNR for parameters suggest that levels A_3, B_2, C_3, and D_1 are better than any other levels of the parameters A, B, C and D respectively.

Table 5 Average SNR table

	Load			
Factor	A	B	C	D
SNR_1	-57.1052	-56.9289	-58.3125	-56.8010
SNR_2	-56.7900	-56.7656	-57.3003	-56.9634
SNR_3	-56.7152	-56.9159	-54.9976	-56.8460
	Tensile strength			
Factor	A	B	C	D
SNR_1	57.1052	56.9289	58.3125	56.8010
SNR_2	56.7900	56.7656	57.3003	56.9634
SNR_3	56.7152	56.9159	54.9976	56.8460

Table 6 shows the summary of ANOVA results indicating the percentage contributions of the control factors to the SNR concerning with the extrusion force and tensile strength. The factors with significant percentage of contribution are shown. Insignificant factor (D) is shown as residuals (error term) in the above table. The tabulated values indicate that the most significant parameter for extrusion force is convex die angle (C) as also observed from Taguchi analysis. The other significant factors are observed to be in the same order as predicted by the Taguchi method with 95% confidence intervals.

Table 6 ANOVA table (Load)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	% Contribution
A	1746	2	873	6.01	0.1427	1.62
B	304.67	2	152.33	1.05	0.4882	0.28
C	1.06E+05	2	52821.33	363.45	0.0027	97.83
Residual	290.67	2	145.33			0.27
Total	1.08E+05	8				100

Fig. 4 shows the main effect plot of the control factors for the extrusion force experiment using the average SNR values from Table 5. It is seen from Fig. 4 that as the control factor C (convex die angle) increases from low level to high level, the average SNR value also increases. The average SNR value is the index of the output or response parameter (extrusion force). Hence, the effect of convex die angle on extrusion force is the most significant as indicated by the steep slope of the line C. In addition to line C, Fig. 4 indicates that the factor A is also significant because its slope is substantial. However, the most dominant factor is the convex die angle (C), followed by billet temperature (A) and mandrel length (B).

4.2 Tensile strength

The main effects of the control factors on tensile strength in terms of SNR are shown in Fig. 5. The average effect of each parameter on tensile strength based on SNR can be seen from this figure, when the control parameters change from one level to another.

Table 7 ANOVA table (Tensile strength)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	% Contribution
A	425.24	2	212.62	9.86	0.0921	11
B	3136.87	2	1568.44	72.7	0.0136	81.16
D	259.55	2	129.78	6.02	0.1425	6.72
Residual	43.15	2	21.57			1.12
Total	3.86E+03	8				100

It is clear from the Fig. 5 that the process parameter mandrel length (B) has more strong effect on tensile strength than the rest of the parameters. The sequence of parameters in the order of significant effects are B, A, D and C. Levels A_2, B_3, C_3 and D_1 appear to be the best choice in terms of mean response and variation as shown in Table 5 and Fig. 5.

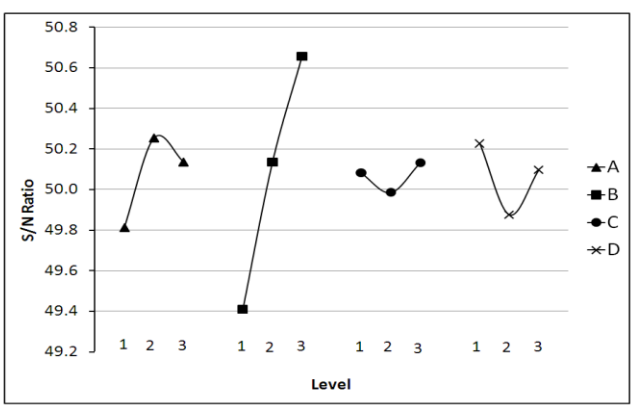

Figure 5 Main effects of control factors on Tensile strength

Table 7 shows the summary of ANOVA results indicating the percentage contributions of the control factors to the SNR concerning with the tensile strength. The factors with significant percentage of contribution are shown. Insignificant factors (C) are pooled down as residuals (error term) in the above table. The tabulated values indicate that the most significant parameter for tensile strength is mandrel length (B) as also observed from Taguchi analysis. The other significant factors are observed to be in the same order as predicted by the Taguchi method with 95% confidence intervals. Fig. 5 shows the main effect plot of the control factors for the tensile strength experiment using the average SNR values from Table 5. It is seen from Fig. 5 that as the control factor B (mandrel length) increases from low level to high level, the average SNR value of tensile strength also increases. The average SNR value is the index of the output or response parameter (tensile strength). Hence, the effect of mandrel length on tensile strength is the most significant as indicated by the steep slope of the line B. In addition to line B, Fig. 5 indicates that the factor A and D are also significant because their slopes are substantial. However, the most dominant factor is the mandrel length (B), followed by billet temperature (A) and tooling temperature (D).

4.3 Optimal factor level settings and confirmation run

It is observed from Table 6 that the significant factors which are responsible for lower extrusion load, in the order of their percentage contribution, are convex die angle (97.83%), billet temperature (1.62%) and mandrel length (0.28%). And from Table 7 these corresponding values in the order of percentage contribution which are responsible for improving tensile strength are mandrel length (81.16%), billet temperature (11%) and tooling temperature (6.72%).

Table 8 Optimum factor level settings

Parameter	Label	Extrusion load (kN)	Tensile strength (kN/mm2)
Billet temperature (°C)	A	420	410
Mandrel length (mm)	B	8	11
Convex angle (°)	C	105	
Tooling temperature (°C)	D		400
Predicted range		-58.2354	44.5874
		-58.9745	45.2546
Confirmation run		-58.6912	44.9945

Percent contribution of pooled error as shown in Table 6 and 7 were found to be less than 1% and therefore it can be claimed that the analysis could effectively identify the significant control factors. Once the significant parameters and their levels are identified, the predicted average optimum values of the response variables (extrusion load, tensile strength) are computed at 95% confidence interval and they were summarized and listed in Table 8 with their optimal factor level settings. Also one can note from Table 8 that the confirmation run values of the response variables are well within the predicted ranges.

5. CONCLUSIONS

The effect of extrusion process parameters (billet temperature, mandrel length, convex die angle, tooling temperature) on extrusion load and tensile strength of porthole-die hot extruded Aluminium alloy (6061) tubes were experimentally investigated using Taguchi design of experiments and analysis methods. The significance of effects of control parameters and their levels in addition to percentage contribution of these effects to response variables variation were determined and quantified using ANOVA. The extrusion load increases with the increase in convex die angle and billet temperature. The extrusion load has little effect with regard to mandrel length within the range of 5 to 11 mm. However, the effect of convex die angle on the extrusion load is dominant among all factors considered. The effect of change of mandrel length is predominantly significant as far as the tensile strength is concerned. However, the effects of billet temperature and tooling temperature are relatively small. And it is worth to note that the effect of increase in convex die angle on tensile strength is insignificant but for reducing the extrusion load its contribution is 97.83%. As far as mandrel length is concerned, it contributed 81.16% for maximizing the tensile strength and very meager 0.28% for minimizing the extrusion load. The optimal control factor level settings for lowest extrusion load and highest tensile strength of hot extruded porthole-die Aluminium alloy (6061) tubes with 95% confidence intervals are (A_3, B_2, C_3) and (A_2, B_3, D_1) respectively. The average values of the response parameters from confirmation experiments are found to be well within the confidence interval of predicted optima of these response parameters.

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