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Modeling and Investigation of the Wall Thickness Changes and Process Time in Thermo-Mechanical Tube Spinning Process Using Design of Experiments

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Abstract

Tube spinning technology is one of the effective methods of manufacturing large diameter thin-walled shapes. In this research, effects of major parameters of thermo mechanical tube spinning process such as preform's thickness, percentage of thickness reduction, mandrel rotational speed, feed rate, solution treatment time and aging treatment time on the wall thickness changes and process time in thermo-mechanical tube spinning process for fabrication of 2024 aluminum spun tubes using design of experiments (DOE), are studied. The statistical results are verified through some experiments. Results of experimental evaluation are analyzed by variance analysis and mathematic models are obtained. Finally using these models, input parameters for optimum production are achieved.

Keywords: Tube Spinning, Process Time, Wall Thickness Changes, Analysis of Variance (ANOVA), Regression, Interaction Effect

1. Introduction

Tube spinning is advanced metal forming process which is used for reducing the wall thickness and increasing the length of tubes without changing their inside diameters. For the tube spinning, there are two different methods, forward and backward tube spinning, depending upon the relative directions of the material flow and the roller travel. In both methods, the work piece is fixed in one position at one end and the remaining length is free to slide along the mandrel.

In the forward tube spinning the roller move away from the fixed end of the work piece and the work metal flows in the same direction as the roller, usually toward the headstock, as shown in **Figure 1**.

In the backward spinning of tubes, spinning metal is extruded beneath the roller in the opposite direction of the roller feed, usually toward the tailstock of the machine.

Kobayashi and Thomson [1] performed an approximate analysis to solve spin-forging problems of tube, dividing the process into drawing and extrusion types. Hasimoto [2] experimentally studied the deformation mechanism of tube spinning with a model material (plasticine) and particularly inspected the strain distribution by using a flow function under the assumption of plan deformation in the circumferential direction. K. M. Rajan and K. Narasimhan [3] investigated the effects of heat treatment of preform material on the mechanical properties of the flow formed part and the validity of using empirical relations in predicting the properties of the flow

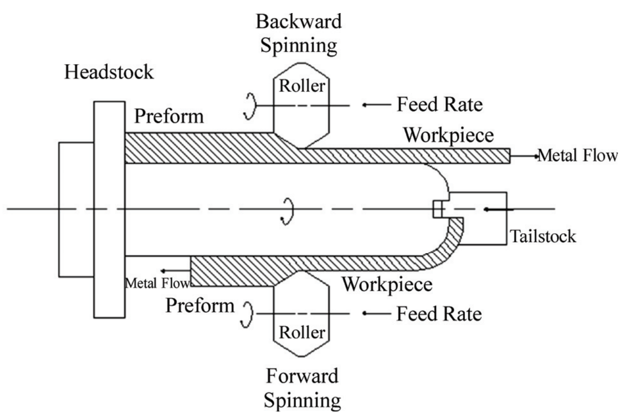

Figure 1. Metal flow and roller travel in forward and backward spinning of tube.

formed components. Y. Xu and S. H. Zhang [4] simulated distributions of stress and strain rate of the deformation by 3D rigid-plastic finite element method. Chang and Wang [5] designed a new thermo mechanical treatment process in the tube spinning for fabricating 2024 aluminum tubes. The designed process can be outlined in sequential order as annealing, first spinning, solution treatment, second spinning and aging. They indicated that annealing and solution treatment can effectively recover the ductility of the spun tube.

In this research, the influences of perform's thickness, percentage of thickness reduction, mandrel rotational speed, feed rate, solution and aging treatment time on process time and wall thickness changes for fabricating 2024 aluminum tubes using DOE has been studied.

It is desirable to know the effects of the major parameters and interactive influences among the process parameters on process time and wall thickness changes and relationship between process time, wall thickness changes and process parameters to obtain the best conditions of parameters for optimum production.

For modeling and determining the influences of main parameters and interaction effects among parameters of the process on time of process and wall thickness changes, DOE method has been employed. The DOE is a statistical method which is used to find the significance of interactive effects among variables and relations among process parameters using variance analysis. Finally, using this model and suitable time of process, input parameters has been achieved for optimum production.

2. Description of Material and Thermo-Mechanical Process

All ductile metals are suitable for tube spinning. We have chosen 2024 aluminum as experimental sample, because it is suitable for tube spinning. The chemical composition of this alloy (work metal) is presented in **Table 1**.

During fabrication, the property of 2024 aluminum tubes must satisfy the spinning operation. Therefore, the preform property requires appropriate heat treatment to increase spin ability or to relieve residual stresses. In this research the thermo mechanical treatment process designed by S. C. Chang and C. C. Wang [5] has been employed.

Five processes of thermo-mechanical treatments which are used in this study are as follows:

1) The original preform is annealed completely in order to unify the microstructure and accomplish the mechanical process with appropriate spinnability. The aluminum tube annealing is conducted in temperature 410℃ for 2 hours [6].

2) The first tube spinning with 5% and 10% reduction rate in thickness was conducted.

3) The solution heat treatment according to the references, the solution heat treatment is performed in the temperature of 490℃ for 60 to 100 minutes. The solution condition was so the transformed structure is recovered and softened for the next operation [6].

4) The second tube spinning with 5% and 10% reduction rate in thickness was conducted.

5) The artificial aging is conducted in 190℃ for 2 or 3 hours which creates the desirable mechanical dimensions and properties in the final tube.

Table 1. The chemical compositions of aluminum alloy 2024.

Elements	Si	Fe	CU	Mn	Mg	Zn	Cr	Ti
Weight(%)	0.19	0.11	2.4	0.51	1.5	0.09	0.01	0.03

3. Experimental Modeling

3.1. The Output Parameters

Output parameters process time and wall thickness changes measured in terms of minute and mm.

3.2. The Input Parameters

Input parameters were selected from the various parameters of spinning such as the properties of the work piece material, tools, mandrel rotational speed, rigidity of machine tools, type of coolant and feed rate of rollers. The selected parameters are:

- The initial thickness of perform part.
- The percentage of thickness reduction.
- The mandrel rotational speed.
- The feed rate of rollers.
- The time of solution treatment and aging.

3.3. The Experiment Conditions

Two rollers made of hardened steel were applied to implement the experiments. The radius of roller tip was 3.5 mm, the roller diameter, 126 mm, the attack angle of roller, 22.5˚ [8], the back angle of roller, 22.5˚ and the internal diameter of preform was equal to the roller diameter.

3.4. The Experimental Design

It is difficult and expensive to perform all experiments. The DOE method can be employed as an efficient technique to accomplish the suitable and necessary experiments with high accuracy. To investigate main and multiple interactions between parameters [7], in this study, a fractional-factorial design was employed with two levels for each parameter (+,–), half fraction with resolution

(VI). **Table 2** shows the input parameters of the process. The procedure includes 32 experiments. The experiments were divided into 2 blocks of 16 experiments in order to eliminate the effects of noise factors (uncontrollable factors), environmental factors (temperature, humidity) and errors that arises from the human sources and measurement tools. Sixteen experiments were conducted in different days.

Since the considered levels for each of the input parameters are two levels, the number of experiments is conducted to determine whether three levels is necessary for each parameter or not which is called the center points. If these points were recognized as the effective points by the analysis of variance, then the experiments should be performed in three levels. **Table 3** indicates the center points. **Figure 2** shows the spun parts. **Figure 3** shows the flow chart of the analysis.

Table 2. The parameter levels.

Parameters	Low Level	High Level
speed of rotational speed (rev/min)v	67	114
feed rate of rollers (mm/rev)f	0.17	0.3
percent of thickness reduction %T	5	10
initial thickness (mm)T	4	6
solution treatment time (min)ts	60	100
aging treatment time (hr)ta	3	4

Table 3. The applied center points in this study.

Run	T (mm)	T %	V (rev/min)	f (mm/rev)	ts (min)	Ta (hr)	Δt (mm)	t (min)
1	4	7.5	90	0.3	80	3.5	–0.261	383.117
2	4	7.5	90	0.3	80	3.5	–0.238	383.17
3	4	7.5	90	0.3	80	3.5	–0.307	383.333

Figure 2. The spun parts.

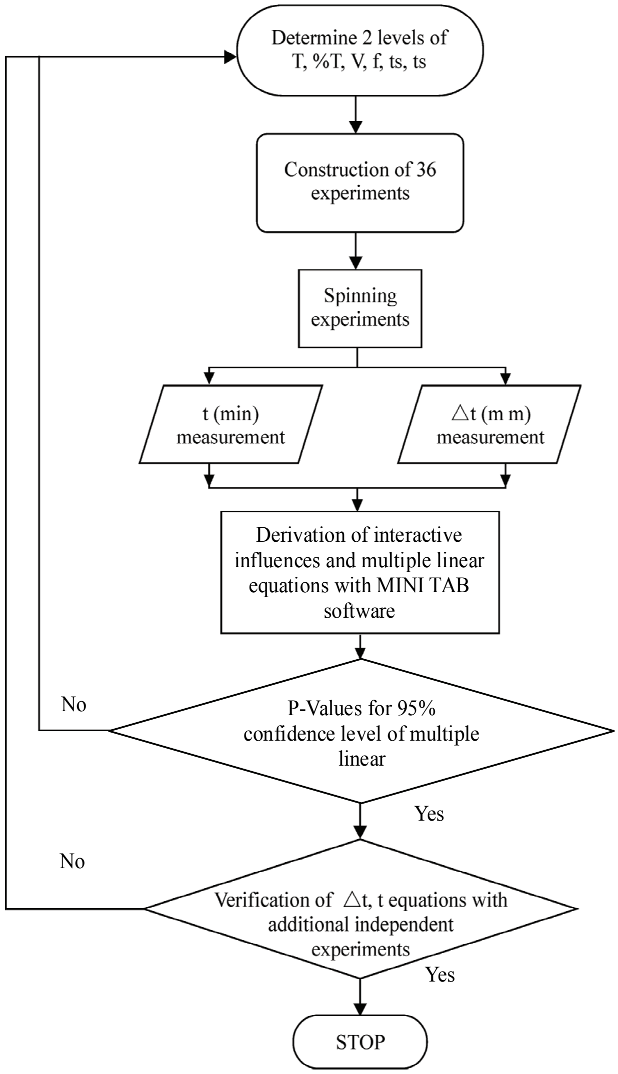

Figure 3. Flow chart of the analysis.

4. Analysis of the Experimental Results

The analysis of variance (ANOVA) is a statistical method to investigate the importance and effect of the parameters. After statistical calculations and implementation of the F-test on the experimental data by ANOVA, probability values of each parameter are extracted from the table of variance analysis. The risk level as considered as 0.05 for the ANOVA.

Once the experimental results are obtained, the coefficients and analysis of variance (ANOVA) are then calculated with MINI TAB software to determine the significance of the parameters, and the P-Values is used to determine which parameter is most significant. The F-ratio test is conducted to check the adequacy for the proposed model. Through experiments, internal diameter growth and wall thickness changes are collected and then fed into a DOE/STAT program to construct statistical regression equations for achieving the initializing of input parameters for optimum production.

4.1. Analysis of the Experimental Results on the Wall Thickness Changes:

After the initial variance analysis and elimination of the unimportant parameters (with low effect coefficient) and use of projection (due to lack of repeat), and with regards to the calculated values of F and P for each one of the effective parameters which is extracted from the table of variance analysis, it can be concluded that the blocking has no important effect on the wall thickness changes (P = 0.830). Therefore we can eliminate this blocking from the variance analysis, and analyze the experiments again (**Table 4**). The risk level of less than 0.05 for parameters in Table 4 shows that the related parameter is significant. Also, in **Table 4** it can be observed that the center points have no effect (P = 0.94).

Therefore, the two levels design is appropriate and we do not need to consider the effective parameters in 3 or more levels. The R squared and the adjusted R squared are shown in bottom of the **Table 4**. Also, the lack of fitness is insignificant which shows the adequacy of the developed model. **Figure 4** indicates the residuals analysis graph of the regression model. As it observed, the residuals have a normal distribution.

Table 4. The variance analysis (ANOVA) for the wall thickness changes.

Parameters	DOF	Adj SS	Adj MS	F_o	P
Main Effects	6	2.828	0.4713	350.10	0.0
2-Way Interactions	8	0.107	0.0134	9.99	0.0
3-Way Interactions	3	0.047	0.0157	11.68	0.0
Curvature	1	0.0	0.0	0.0	0.94
Residual Error	16	0.0215	0.0013		
Lack of Fit	14	0.019	0.0013	1.10	0.57
Pure Error	2	0.002	0.0012		
Total	34				
R-Sq = 99.29%			R-Sq(adj) = 98.49%		

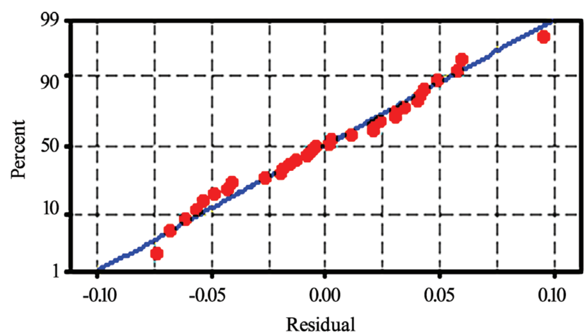

Figure 4. Residuals analysis graph of the regression model.

Figure 5 shows the graphs of each input parameter effect on the wall thickness changes. Also, **Figure 6** indicates interactions effects of the parameters on the wall thickness changes.

Figure 6 shows that for the wall thickness changes there are significant interactive influences among initial thickness and percentage of thickness reduction, feed rate of rollers and solution treatment time, mandrel rotational speed and aging treatment time.

Also, thinner of initial thickness, small percentage of thickness reduction, slower mandrel rotational speed, lower solution treatment time and higher of feed rate of rollers lead to smaller wall thickness changes.

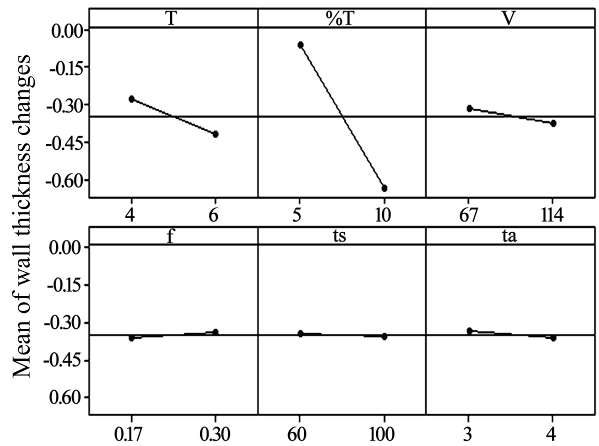

Figure 5. The graphs of mean parameter effect on the wall thickness changes.

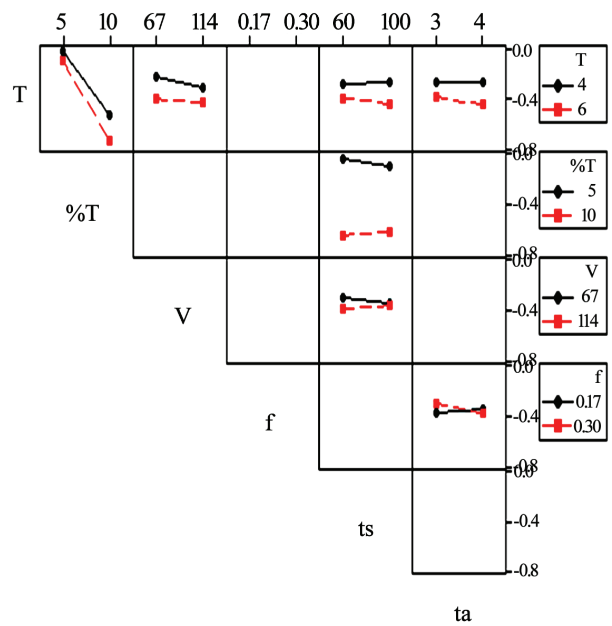

Figure 6. The graphs of the parametric interactions effect on the wall thickness changes.

Figure 7 summarizes the initial thickness on the wall thickness changes of tube spun at percentage of thickness reduction. The result shows that decrease of initial thickness combined with the decrease of percentage of thickness reduction produces small wall thickness changes of the spun tube.

Reasonably, the thicker the initial thickness and deeper the percentage of thickness reduction , the more energy is required for the material to deform and the deformation is contributed to the vicinity of the inner surface as the material flows in the radial direction and wall thickness changes tube spun increase.

Figure 8 shows effect of mandrel rotational speed on the wall thickness changes of tube spun at various initial thicknesses. Reasonably, at the slower mandrel rotational speed, the deformation is confined only to the vicinity of the outer surface as the wall thickness changes of tube spun decrease.

4.2. Analysis of the Experimental Results on the Process Time

After the initial analysis of variance, elimination of the unimportant parameters (with low effect coefficient) and using projection (because of the few iterations), it can be concluded that the blocking has no important effect on the process time (P = 0.369), therefore we can eliminate this blocking from the analysis of variance and analyze the experiments again (**Table 5**). Also it means that the experimental condition is fixed and the out-of-control parameters such as temperature and humidity have no effect on the experiments.

After elimination of blocking and applying the analysis of variance (**Table 5**), we observed that the center points have effect (P = 0). Therefore, the design of experiments is not correct and there is need to consider the mean input parameters in 3 or more levels. Another parameter which is very important in table ANOVA is the lack of fitness which shows the correctness of regression analysis of the process time. The ineffectiveness of this parameter (P = 0.312) guarantees the integrity of the Analysis.

Figure 9 indicates the residuals analysis graph of the regression model. As it observed, the residuals have a normal distribution.

Figure 10 shows the graphs of each input parameter's effect on the process time. Also, **Figure 11** indicates interaction effects of the parameters on the process time.

As it was shown any parameter has not interaction effects on the others, then each parameter is considered through the mean effect graph. Also, this graph indicates that all input parameters affect process time. According to **Figure 9**, the process time decreases as a result of increasing the initial thickness, mandrel rotational speed, feed rate of rollers and decreasing of the percentage of

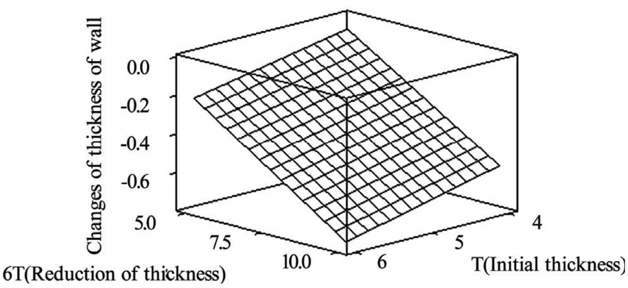

Figure 7. Effect of the initial thickness on the wall thickness changes of tube spun at percentage of thickness reduction.

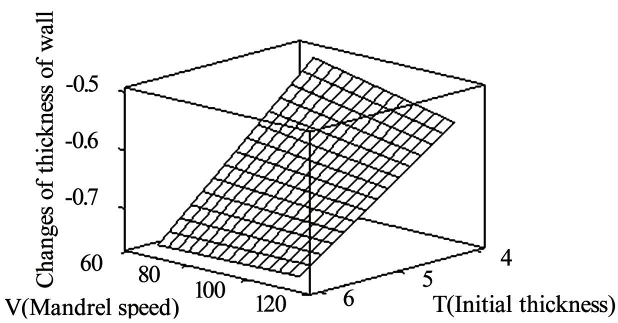

Figure 8. Effects of mandrel rotational speed on the wall thickness changes of tube spun at various initial thicknesses.

Table 5. The variance analysis (ANOVA) for the process time.

Parameters	Dof	Adj SS	Adj MS	F_o	P
Main Effects	6	45184.7	7530.79	26098	0.0
2-Way Interactions	11	96.9	8.81	305.2	0.0
3-Way Interactions	5	3.8	0.77	26.63	0.0
Curvature	1	4.5	4.50	155.8	0.0
Residual Error	11	0.3	0.03		
Lack of Fit	9	0.3	0.03	2.56	0.312
Pure Error	2	0.0	0.01		
Total	34				

R-Sq = %100.00 R-Sq(adj) = %100.00

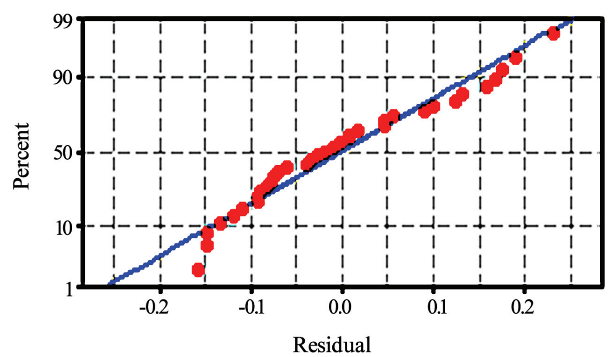

Figure 9. Residuals analysis graph of the regression model.

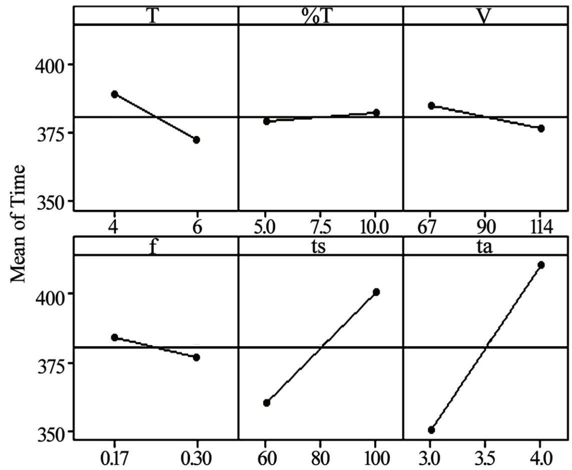

Figure 10. The graphs of mean parameter effect on the process time.

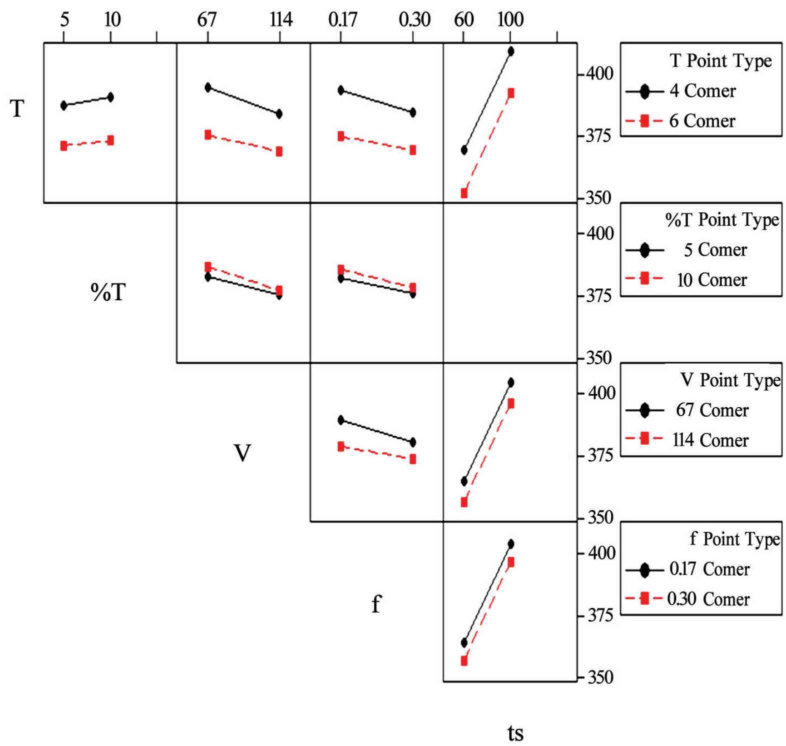

Figure 11. Interaction effects of the parameters on the process time.

thickness, solution treatment time and aging treatment time.

5. The Predictor Model of Wall Thickness Changes and Process Time

Finally, two hierarchical models were developed for wall thickness changes and process time by multiple linear regression technique. The insignificant terms were removed from the model and the final models were developed with significant terms which were determined by ANOVA Equation (1) for wall thickness changes and (2) for process time.

$$\begin{aligned}\Delta t &= -21.6194 + 0.1163(\%T) + 0.6239(T) + 13.1253(f) \\ &- 0.0066(V) + 0.4012(ta) + 0.249(ts) - 0.0525(T \times \%T) \\ &- 2.101(T \times f) - 0.846(\%T \times f) - 0.7415(f \times ta) \\ &+ 0.0004(\%T \times ts) + 0.00003(V \times ts) - 0.0032(T \times ts) \\ &- 0.0014(ts \times ta) + 0.0006(T \times V) - 0.0286(T \times ta) \\ &- 0.0523(f \times ts) + 0.1692(T \times \%T \times f) + 0.109(T \times f \times ts)\end{aligned} \quad (1)$$

$$
\begin{aligned}
t(\mathrm{min}) &= 6602.36 + 59.73(ta) + 1.014(ts) - 1296.31(T) \\
&- 71.29(V) - 266.81(f) + 2(\%T) + 14.20(T \times V) \\
&+ 1.68(V \times f) + 33.75(T \times f) - 0.0066(\%T \times V) \\
&- 0.14(T \times \%T) - 1.45(\%T \times f) - 0.0001(V \times ts)253(T \times V) \\
&- 0.157(V \times ts) + 54.78(T \times \%T \times f) - 0.75(T \times ts \times ta) \\
&+ 0.0147(T \times V \times ts)
\end{aligned} \quad (2)
$$

In order to check the reliability of the equations induced through regression analysis, independent experiments with process parameters different from the 35 assigned experiments, are selected. **Table 6** demonstrates the comparison of the prediction data derived from Equation (1) with the experimental results. The verification of the results shows that the developed models have acceptable error. From the results, it is sound that, the prediction error ranged within 13.63%.

The verification of the results, **Table 7**, shows that the developed models have acceptable error. From the results, it is sound that, the prediction error ranged within 1.11%.

6. Conclusions

In the present study, the thermo mechanical tube spinning process has been optimized by selection of significant input parameters including the initial thickness of preform, percentage of thickness reduction, mandrel rotational speed, feed rate of rollers, solution treatment time and aging treatment time. Finally, by means of ANOVA, the main effects of the input parameters and their interactions on the wall thickness changes and process time were determined. Based on the statistical analysis of the experimental data the following conclusions can be obtained.

1) With regards to the variance analysis and the effect of interactions between the input parameters, it can be concluded that with the thinner initial thickness, small reduction rate of thickness, lower solution treatment time, slower mandrel rotational speed and higher feed rate of rollers, the wall thickness changes decrease, as a result the wall thickness changes reaches a suitable level.

2) Also for process time, it was shown any parameter has not interaction effects on the others, and each parameter is considered through the mean effect graph. Also, all input parameters affect process time and the process time decreases as a result of increasing the initial thickness, mandrel rotational speed, feed rate of rollers and decreasing of the percentage of thickness, solution treatment time and aging treatment time.

3) In the thermo mechanical tube spinning process, blocking have insignificant effects on the wall thickness changes and process time. It means that noise factors (uncontrollable) have no effect on spinning process.

4) In the thermo-mechanical tube spinning process center points have insignificant effects on the process time and the wall thickness changes. It means that process can be modeled with two levels for each input parameters.

5) Finally, with regards to the large number of effective parameters in the tube spinning thermo-mechanical process, consideration of the tube spinning through the design of experiments is shown to be the efficient method for achieving the acceptable results.

Table 6. Experiments that were implemented to affirm the equation relate to the wall thickness changes.

Run	Parameters						Results		Error (%)
	T	%T	V	f	ts	ta	Exp.	Mod.	
1	6	8	82	0.3	90	3.5	-0.45	-0.48	6.25
2	4	7	94	0.17	70	3.75	-0.218	-0.24	9.16

Table 7. Experiments that were implemented to affirm the equation relate to the process time.

Run	Parameters						Results		Error (%)
	T	%T	V	f	ts	ta	Exp.	Mod.	
1	6	8	82	0.3	90	3.5	379	380.6	0.26
2	4	7	94	0.17	70	3.75	395.4	397	0.4

7. References

[1] S. Kobayashi and E. G. Thomson, "Theory of spin forging," China Institute for Radiation Protection Annalen, Vol. 10, pp. 114-123, 1961-1962.

[2] H. Hasimoto, S. Kita, T. Shibasaka and S. Yoshida, "On the deformation in tube spinning," Himegi Industrial University Report, No. 33A, 1980.

[3] K. M. Rajan and K. Narasimhan, "Effect of heat treatment of prefom on the mechanical properties of flow formed AISI 4130 Steel Tubes—a theoretical and experimental assessment," Journal of Materials Processing Technology, Vol. 125-126, pp. 503-511, 2002.

[4] Y. Xu and S. H. Zhang, "3D rigid-plastic FEM numerical on tube spinning," Journal of Materials Processing Technology, Vol. 113, pp. 710-713, 2001.

[5] S. C. Chang and C. C. Wang, "Fabrication of 2024 aluminum spun tube using a thermo mechanical treatment process," Journal of Materials Processing Technology, Vol. 108, pp. 294-299, 2001.

[6] American Society for Metals Handbook, Vol. 4: Heat Treating, American Society for Metals International, 2nd edition, 1994.

[7] D. C. MontGomery, "Design of experimentals & statistica modeling," McGrow Hill Incorporation, New York, 2005.

[8] Z. E. Ma, "Optimal angle of attack in tube spinning," Journal of Materials Processing Technology, Vol. 37, pp. 217-224, 1993.

