An investigation on the effective parameters and optimal design in ECAP-Conform process of commercially pure titanium using statistical and numerical approaches

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Abstract:
The Equal Channel Angular Pressing-Conform (ECAP-Conform) process has improved the mechanical and functional properties of materials as well as resolves the disadvantages of conventional ECAP. The main goal of this study was investigation of the variable in ECAP-Conform process of pure titanium Grade 2. The design of experiments with full factorial technique was implemented in conjunction with finite element numerical simulation. The equivalent plastic strain, required torque, applied force on the ECAP die, and the warping radius of the product were measured and results were interpreted using analysis of variance. It was found that the ECAP die angles and the rod bending angle have the highest effect on both imposed strain and required torque. Also, the rod bending angle and the rod-die friction had no significant effect on the warping radius. The optimal values were specified for minimizing the required torque, reaction force, and warping radius, and maximizing the imposed strain. Based on the optimal estimated parameters, the minimum values of torque, force, warping radius, and maximum value of equivalent strain were predicted to 8.4 kN.m, 42 kN, 0.36 m, and 1.7, respectively. Also, the response optimizer obtained the results with less than 8% error in comparison with numerical simulation.

Keywords:
ECAP-Conform Process; Commercially Pure Titanium; Optimization; Design of Experiment; Finite Element Method

1. Introduction

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In the last decades, severe plastic deformation (SPD) methods have been frequently used to produce ultrafine-grained (UFG) materials with unique mechanical and physical properties. This method includes various forming techniques to impose very high strains on materials leading to grain refinement [1]. Among the SPD methods, equal channel angular pressing (ECAP) due to obtaining the homogeneous microstructure and giving a strain of about 1 on each pass through the die has attracted the most attention [2]. The ECAP process in its original or conventional design has disadvantages that related to the length of the workpiece, (1) the aspect ratio of the workpiece should be smaller than the critical value so buckling does not occur and (2) limitation in the stroke of the press ram [3]. The other difficulty that makes this process with low production efficiency and high cost is the discontinuity of the process. Also, the length near each end of the workpiece usually contains the non-uniform structure and has to throw away. Many attempts have been made to remove these limitations, such as the equal-channel angular drawing (ECAD), the accumulative roll-bonding (ARB), the repetitive corrugation and straightening (RCS), the Conshearing, the continuous constrained and strip shearing (C2S2), and the equal channel angular pressing (ECAP)-Conform [4].

Volokitina et al. investigated the finite element (FE) modeling to combine the ECAP and drawing processes (ECAP-Drawing) for bimetallic wire deformation. It was found that the stress state of both materials was different in both deformation zones. The deformation in the ECAP zone was divided into sections of tension and compression, diagonally while the deformation in the drawing zone is completely symmetrical [5]. Krajňák et al. have introduced a new SPD technique known as the RCB (Rotational Constrained Bending). They investigated the plastic deformation distribution and microstructure of commercially pure titanium (grade 4). Results showed that the grain size decreased to 400 nm, and the tensile strength increased after four passes by about 15% [6]. Another novel technique has been introduced by Gorji et al. as an SPD method that combines the Extrusion and ECAP processes (C-Ex-ECAP). They investigated the microstructure, mechanical and electrical properties of the copper workpieces. Results showed that the yield strength and hardness of samples increased, and electrical conductivity was reduced by this new method [7]. In 1974, Etherington introduced a new idea, Conform, for the continuous extrusion of metals. In this process, wires or powders as feedstock were formed into the shape of a groove on a roller. Frictional driving force provided from contact between three surfaces of the groove with feedstock, pushed the feedstock on to outlet. The stationary die covers the groove and causes the dragging frictional force by contact interface between the feedstock and stationary die. The cross-section of the outlet has usually a different shape from the groove. Conform process aims to change the geometry of the workpiece or consolidate the powders with only one process pass [8].
The ECAP-Conform process is a combination of the Conform and ECAP processes to produce UFG material continuously. In this process, the stationary constraint dies limits the movement of the workpiece and forces it to turn an angle by shear as in a regular ECAP process. In the ECAP-Conform, in addition to the continuous nature of the process, the workpiece plastically bends before entering into the shear zone of the die. If the initial cross-section of the workpiece is different from the groove cross-section, the ECAP-Conform process will plastically deform the workpiece and will match it with the groove cross-section. Figure 1 shows a schematic of ECAP-Conform along with the main characteristic parameters namely the die channel angle (\(\phi\)), the die outer corner angle (\(\psi\)), the rod bending angle on the roller (\(\alpha\)), and the warping radius of the formed rod (\(R\)).

Raab et al. [4] were used the ECAP-Conform to obtain ultrafine-grained commercially pure aluminum wire at room temperature. In their work, the aluminum wire processed up to four passes via ECAP-Conform die with a channel angle of 90°. Their observations showed that after one to two passes, dislocations and low angle grain boundaries were formed, and after four passes of ECAP-Conform the grain size of almost 650 nm was obtained. Also, the yield strength and the ultimate strength increased by the ECAP-Conform process significantly, while the elongation to failure remained in the range of 12-14%. Subsequently, Raab et al. [9] succeed to perform the ECAP-Conform on the commercially pure titanium (CP-Ti) up to 6 passes and decrease the grain size to the range of 200-300 nm. Hoppel et al. [10] used the ECAP-Conform of 6061 aluminum alloy rods and investigated the homogeneity, shear strength, and anisotropy of the product utilizing Vickers microhardness testing. The results showed that after a single pass, the inhomogeneity of the workpiece increases both on the cross-section plane and longitudinal direction. While, after four passes the distribution of the hardness will be uniformed, and the inhomogeneity will significantly reduce. Parsa et al. investigated the effect of the groove path of the Conform process on the microstructure and properties of 1100 aluminum numerically and experimentally. They demonstrated that by increasing the groove path, the strain penetrated to the specimen which caused non-uniform strain distribution in the deformed sample [11]. In another work, Parsa et al. have investigated the microstructural of AA 1100 rod and found that after one pass ECAP-Conform process, the grain sizes were not changed extremely and were mostly elongated. On the other hand, the strength of the material had increased due to an increase in the dislocation densities and formation of subgrains [12]. Mechanical properties and electrical conductivity of Al-Mg-Zr alloy after ECAP-Conform and cold drawing were investigated by Murashkin et al. [13]. Results showed that this process increased ultimate strength from 129 MPa to 267 MPa accompanied by a good electrical conductivity. Morozova et al. have investigated the
microstructural of a Cu-0.1%Cr-0.1%Zr alloy after the ECAP-Conform process. It was found that during deformation the high-angle boundaries (HAB) transformed to low-angle boundaries (LAB) due to the strain-induced of the ECAP-Conform process [14]. Shahab et al. [15] compared the distribution of equivalent plastic strain after the continuous confined strip shearing (C2S2) and the ECAP-Conform processes for 1100 Al numerically. The results showed that during the C2S2 process the sample experienced the equivalent plastic strain of 0.13 at the initial stage of bending gradually, while during the ECAP-Conform process the strain magnitude of about 0.52 would suddenly impose. So, the ECAP-Conform process can produce a finer microstructure in the same conditions. The ECAP-Conform process simulation of AA 6061 was performed to investigate the effects of die channel angle and friction on the strain and the torque by Gholami et al. [16]. They have examined different channel angles of 90°, 100°, and 110°, in addition to various friction conditions. The results showed that by increasing the channel angle from 90° to 110°, the amount of plastic strain and the required processing torque was reduced about 40% and 50%, respectively. Besides, more strain homogeneity was observed at the higher channel angle. Thermo-mechanical ECAP–Conform process of 6082 aluminum was carried out by Procházka et al. [17]. Local mechanical properties were estimated by miniaturized tensile testing techniques. The hardness and tensile test results showed that the microstructure of samples had inhomogeneity, which was a consequence of the significant strain differences applied in the upper and bottom of the aluminum wire. Required torque in the ECAP-Conform process was investigated by Gerdooei et al. [18], theoretically and numerically. They calculated the torque of the ECAP-Conform process by using the energy balance and the upper-bound methods. Also, they compared the results of their theory with numerical simulation and observed the acceptable compliance. Subsequently, Gerdooei et al. have performed an analytical and experimental study of the required torque of the ECAP-C process with a square cross-section (for CP-Ti Gr.2). Also, they have presented a slip threshold criterion (STC) for performing the ECAP-C process successfully. There was a difference of about 11% between analytical and experimental method [19].

Nevertheless, the most implemented experimental and numerical studies were related to ECAP-Conform of aluminum alloys, and few types of research have been carried out on CP-Ti grade 2. Additionally, in the literature, no comprehensive research was found on the evaluation of effective parameters of the ECAP-Conform. Therefore, in the present study, the full factorial design of the experiment (DOE) is used to investigate the effect of process parameters such as friction, die angles, and the rod bending angle. The response factors are the amount of imposed plastic strain, the required torque, the reaction force, and the warping radius of the product. Finally, the ECAP-
Conform machine is manufactured according to the optimal values of these parameters.

2. Materials and methods

2-1. Finite element model

The explicit dynamics procedure in Abaqus/Explicit was used to model the ECAP-Conform process of the CP-Ti grade 2. Figure 2 illustrates the prepared 3D finite element model of this process. The raw material has a circular cross-section of 8 mm diameter with 400 mm length. The material behavior was assumed elastic-plastic which included a density of 4510 kg/m3, Poisson’s ratio of 0.37, and an elastic modulus of 105 GPa. The true stress-strain curve of CP-Ti which was obtained from the compression test according to the ASTM-E9 standard is shown in Figure 3. The CP-Ti rod was deformed by employing a roller with 300 mm diameter having a constant rotational velocity of 0.05 rad/s. To reduce the runtime, in addition to employing the mass scaling technique, half of the rod was modeled due to its symmetrical geometry. The contact condition of components was modeled by a surface-to-surface contact along with Coulomb’s friction law. The effect of friction condition is considered by employing three different friction coefficients of 0.2, 0.3, and 0.4. According to Figure 2, the symmetrical boundary conditions for the rod and fixed reference points for other tools were applied as geometrical constraints in the model. The rod was meshed by using C3D8R (an 8-node linear brick with reduced integration) elements with optimal element size of 1 mm obtained from mesh sensitivity analysis. Also, the other discrete rigid tools meshed with R3D4 (4-node 3D bilinear rigid quadrilateral) elements. At the beginning of the simulation, the rod is bitten by the roller, due to significant friction between the rod and the groove of the roller. This frictional driving force itself pushed the rod on to the outlet without needing any extra pre-load or mandatory boundary condition.

2-2. Design of experiments

This research aims to understand and predict the effect of the input process parameters on the response of the ECAP-Conform process using a full factorial experiment design. The four independent factors involved friction coefficient between the rod and the roller ($\mu$), the die channel angle ($\varphi$), the die outer corner angle ($\psi$), and the rod bending angle on the roller ($\alpha$). Also, the four response parameters were the equivalent plastic strain (PEEQ), the required torque (T), the applied reaction force on the ECAP die (F), and the warping radius of the formed rod (R). The parameters and their related levels are shown in Table 1. The number of experiments will be equal to $3^3 \times 2^1 = 54$.  

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The maximum amount of required process torque and the maximum applied force to the ECAP die were measured at the reference points of the roller and the die, respectively. Also, after exiting the rod from the ECAP die, the maximum effective plastic strain created at the cross-section of the rod was measured at 20 mm distance from the rod face. Furthermore, as shown in Figure 4, the coordinates of three points with equal distances of 30 mm and sufficient distance from the rod face were recorded. Finally, by fitting an arc through these three points, the warping radius of the rod was measured.

3. Results and discussion

3-1. Validation of FEM results

To validate the FEM results, a comparison between numerical simulation and theoretical relation for the equivalent plastic strain has been conducted. Iwahashi et al. calculated the equivalent plastic strain during ECAP by equation 1 [20]:

$$\varepsilon = \frac{N}{3 \sqrt{3}} \left[ 2\cot \left( \frac{\varphi + \psi}{2} \right) + \psi \csc \left( \frac{\varphi + \psi}{2} \right) \right]$$

(1)

where N is the number of passes, \( \varphi \), and \( \psi \) are the die channel and the die outer corner angle, respectively. Also, the maximum equivalent plastic strain during bending can be calculated by equation 2 [21]:

$$\varepsilon = \frac{2}{\sqrt{3}} \frac{c}{\rho}$$

(2)

where \( c \) is the radius of the rod and \( \rho \) is the radius of the roller. The summation of the abovementioned relations will give the total strain of the rod after ECAP-Conform. By replacing the die channel angles of 90°, 105° and 120°, and \( \psi = 30° \) in Eq. 1, as well as \( c = 4 \) mm and \( \rho = 150 \) mm in Eq. 2 the imposed strain would be equal to 1.048, 0.838, and 0.655, respectively. In Figure 5 results of the PEEQ for different die channel angles obtained by numerical and analytical methods are compared together. It can be seen that for all die channel angles the analytical method gives a strain smaller than the FEM result. Also, the higher the channel angle the lower the strain. The difference may be due to the lack of friction consideration in the simple theoretical approach, which plays a key role in the ECAP-Conform. Similar justifications were also mentioned in other researches [16,20,22].

3-2. Analysis of variance
Statistical analysis is performed to understand the main effects and interactions of effective parameters during the ECAP-Conform process. The final aim is to determine their optimum range to maximizing imposed strain and minimizing required torque and force, in addition to producing a rod with a minimum warping radius. The analysis of variance (ANOVA) method is employed as a useful statistical method to scientifically interpret the interaction of parameters. By investigating the equality of variances and normality distribution of the data, one can deduce the ANOVA results are valid. Plots of normal probability versus residual and residual versus fitted value will verify these assumptions. In Figure 6 these plots are shown for one of the responses namely PEEQ.

Furthermore, the degrees of freedom, the adjusted sum of squares, and mean squares obtained by analysis of variances for PEEQ are presented in Table 2. A model will be significant when the amount of its p-value is less than 0.05 (by considering a confidence level of 95%). Regarding the ANOVA table, the die channel angle and the rod bending angle on the roller have the highest effect among the studied input parameters on PEEQ with 32.86% and 16.47% contributions, respectively. On the other hand, the 2-way and the 3-way interactions of input parameters are not significant.

Table 3 presents the ANOVA table for the required torque. It is shown that all of the input parameters have a significant effect on the response, while the rod bending angle has the highest effect on the required torque with a 24.67% contribution. Results indicate that some of the 2-way and the 3-way interactions of input parameters are not significant. Also, exist significant interaction effects between die angles and rod bending angle. The extent of the contribution in linear, 2-way interaction, and 3-way interaction was 55.54%, 23.15%, and 14.93%, respectively.

The ANOVA table for the applied reaction force is offered in Table 4. It is observed that among the investigated factors the die outer corner angle, the die channel angle, and the rod bending angle have the most effect on the reaction force with 29.48%, 13.68%, and 13.27% contribution, respectively. Also, the friction between the roller and the rod as well as the 2-way and 3-way interactions have not considerable effect on the applied force.

According to Table 5 representing ANOVA for the warping radius, the most important parameters are the die channel angle and the die outer corner angle with 58.39% and 17.92% contribution, respectively. Additionally, the interaction of these factors ($\phi \times \psi$) with 11.56% contribution is also significant.

Based on the abovementioned ANOVA results, the contribution value of each process parameter (only the main effects) on the response variables can be summarized graphically in Figure 7. It was found that the rod bending
angle on the roller (\(\alpha\)) and the friction coefficient between the rod and the roller (\(\mu\)) have no effect on the warping radius of the outlet rod. It can be also seen that the die channel angles (\(\varphi, \psi\)) affect on all four response parameters. Also by investigating the aforementioned ANOVA tables observed that the die channel angle, the die outer corner angle, and the rod bending angle are the three effective factors on the target variables of the ECAP-Conform process. Therefore, the main effects and interactions of these parameters will be evaluated individually in the following sections.

3-3. Main effects

It has been previously stated that the ECAP dies to have two effective angles: first, the die channel angle (\(\varphi\)) (usually between 90° to 150°), and second, the die outer corner angle (\(\psi\)) (usually in the range of 0° to 90°). Figure 8 shows the main effects of the die channel angle on PEEQ, required torque, reaction force, and the warping radius of the formed rod. Results clearly show that by increasing the die channel angle all responses parameter will reduce.

Similar to the abovementioned procedure the main effects of the other responses were obtained. But to summarize the outcomes will be discussed briefly, and the main effect plots of the other factors were omitted. For the die outer corner angle, the main effect plots showed that increasing \(\psi\) from 0° to 60° will decrease the warping radius by almost about 30%. Also, by increasing \(\psi\) from 0° to 30°, the PEEQ decreases and the reaction force and the required torque increases, while the trend of the results will be opposite after more increase in \(\psi\) up to 60°. In fact, in this condition, PEEQ increases, and the required torque and reaction force decreases, due to interaction effects between parameters.

From the main effect plots of rod bending angle, it can be deduced that when \(\alpha\) increases from 60° to 90° the warping radius and PEEQ of deformed rod increase by 1.5% and 18% respectively. On the other hand, it will reduce the required torque and the reaction force.

3-4. Interactions between factors

Interaction between factors exists when it is found that the difference in response between the levels of one factor is not the same at all levels of the other factors [23,24]. If the interaction is large, the corresponding main effects will be less important. From the ANOVA tables, these effects are recognizable.

Regarding P-values and contribution percent in ANOVA tables, one can deduce the interaction between \(\varphi, \psi, \) and \(\alpha\)
for required torque (Table 3) should be considered. As well, for the warping radius, only a 2-way interaction of $\varphi$ and $\psi$ is important (Table 5). Figure 9 shows the interaction plot of $\varphi$, $\psi$, and $\alpha$ for the required torque. The investigation of these plots along with the ANOVA table of the torque (Table 3) indicates that the contribution for 2-way interactions of $\varphi \times \psi$, $\varphi \times \alpha$, and $\psi \times \alpha$ were 9.07%, 7%, and 4.81%, respectively.

Also, the 3-way interaction of $\varphi \times \psi \times \alpha$ had 8.57% contribution. Therefore, as can be seen in Figure 7 the 2-way interaction of $\varphi \times \psi$ has the highest effect on the response. For the other parameters, 2-way and 3-way interactions do not have a significant effect; therefore, as mentioned before examining their main effects is sufficient.

### 3-5 Optimal levels

The goal of the optimization in the ECAP-Conform process is to minimize the required torque, the reaction force, and the warping radius, in addition to maximizing the amount of imposed equivalent plastic strain after ECAP. But in practice, it is not possible to gain the optimal amounts for all of the responses due to the reverse effects of process parameters on each response. In other words, the improvement of one response has an inevitable negative effect on another one. Therefore, the next step is to select the optimal levels to obtain the maximum desirability; i.e. all responses achieve an acceptable level of satisfaction. Response optimization can be utilized to find the best combination of parameters that optimize a single response or a set of responses. For this purpose, the “response optimizer” in Minitab software was employed for this optimality evaluation. This software by considering the Individual and composite desirability selects the best response. The value of desirability has a range of zero to one and one represents the ideal case. Equation 3 shows the relation between individual desirability ($d$) and composite desirability ($D$) as follows:

$$D = \left(d_1 d_2 \cdots d_m \right)^{\frac{1}{m}}$$  \hspace{1cm} (3)

Table 6 shows the optimal levels for each parameter based on this method.

Regarding all responses associated with the reported values in Table 6, the overall desirability achieved 0.85. Based on the response optimization results, the minimum torque, force, and warping radius obtained by selected values are predicted to 8.4 kN.m, 42 kN, 0.36 m, respectively; while the maximum imposed strain of 1.7 was obtained. Also, the FE simulation of ECAP-Conform by using these optimized values led to the required torque, applied force,
warping radius, and PEEQ of 7.5 kN.m, 36 kN, 0.37 m, and 1.8, respectively.

The mean error of the optimal value compared to the FE simulation is about 8%. Equation 4 was used to calculate the error percentage. In this regard, $\Delta_{\text{Minitab}}$ and $\Delta_{\text{FE}}$ are Minitab and FE outputs, respectively.

\[
\text{error \%} = \left( \frac{\Delta_{\text{Minitab}} - \Delta_{\text{FE}}}{\Delta_{\text{FE}}} \right) \times 100
\]  

(4)

According to optimal values, the set-up of the ECAP-Conform machine was fabricated, as shown in Figure 10, and the process was performed for CP-Ti grade 2. The ECAP-Conform machine was designed with the ability to adjust the roll bending angle ($\alpha$) from 60° to 270° (by embedding six stationary supports).

The microstructure of the as-received CP-Ti and CP-Ti after one pass ECAP-Conform process was investigated by the field emission scanning electron microscope (FESEM). Firstly, samples are cut perpendicular to the direction of ECAP-Conform and after cold-mounting, their surface is polished. Then, to clarify the grain boundary, samples were etched up to 140 seconds in a Kroll solution ($1 \text{ ml HF} + 5 \text{ ml HNO}_3 + 44 \text{ ml H}_2\text{O}$). Figure 11 shows the FESEM images for as-received CP-Ti and CP-Ti after one pass ECAP-Conform process. As-received titanium has an equiaxed structure with an average grain size of 4 μm. After performing one pass of the ECAP-Conform process, this structure will be elongated due to severe plastic deformation. The average grain size of titanium after performing one pass of the ECAP-Conform process is 2.5 μm and 1.3 μm in the longitudinal and transverse directions of the grain, respectively. Indeed, about 67.5% and 37.5% reduction in grain size occurs in the transverse and longitudinal directions, respectively.

4. Conclusions

In this research, FEM simulation of ECAP-Conform for CP-Ti grade 2 was conducted, and the effect of process parameters including friction condition, die channel angle, die outer corner angle and the bending angle was examined on the required torque, reaction force, imposed strain, and warping radius of the specimen at the outlet. The following results are obtained using the statistical analysis of variance:

- Among the all studied parameters, the die channel angle ($\varphi$) and the bending angle ($\alpha$) have the greatest effect on the amount of imposed strain. By increasing $\varphi$ from 90° to 120°, PEEQ at outlet cross-section
lowered about 28%. Also, when $\alpha$ increases from 60° to 90°, PEEQ will improve by 18%.

- All investigated factors have a meaningful effect on the required torque, especially the rod bending angle ($\alpha$) and the outer corner angle ($\psi$) has the highest effect on the required torque with 24.67 % and 17.1% contribution, respectively.
- The friction coefficient would only influence the required torque significantly, and its effect on the other response is negligible.
- ECAP die angles i.e. $\varphi$ and $\psi$ exert the most effect on the warping radius of the specimen by 58% and 18% contribution. The main effect plot of $\varphi$ revealed that the higher the channel angle the lower the warping radius. It should be noted that the 2-way interaction between $\varphi$ and $\psi$ has a significant effect with an 11.51% contribution.
- The 2-way and the 3-way interactions of input parameters are not significant for PEEQ and reaction force; although, they are important for required torque with 24.31% and 16.77% contribution, respectively.
- The optimal values for friction coefficient, channel angle, outer corner angle, and rod bending angle were 0.2, 120°, 0°, and 90° respectively. The predicted values by these adjusted factors were the required torque 8.4 kN.m, reaction force 42 kN, 0.36 m of warping radius, and 1.7 of imposed strain.

Compliance with Ethical Standards

We declare that there is no conflict of interest in submitting this manuscript and approved by all authors for publication. The manuscript submitted was the original research that has not been published formerly and is not under consideration for publication elsewhere.

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### Table 1

| Parameter                                             | Level 1 | Level 2 | Level 3 |
|-------------------------------------------------------|---------|---------|---------|
| Friction coefficient between rod and roller ($\mu$)    | 0.2     | 0.3     | 0.4     |
| Die channel angle ($\varphi$)                         | 90°     | 105°    | 120°    |
| Die outer corner angle ($\psi$)                        | 0°      | 30°     | 60°     |
| Rod bending angle on the roller ($\alpha$)             | 60°     | 90°     | -       |

### Table 2

| Source                  | DF  | Seq. SS | Cont. % | Adj. SS | Adj. MS | P-Value |
|-------------------------|-----|---------|---------|---------|---------|---------|
| Model                   | 37  | 4.89308 | 89.52   | 4.89308 | 0.132245| 0.006   |
| Linear                  | 7   | 2.95958 | 54.15   | 2.71858 | 0.388368| 0.000   |
| $\varphi$               | 2   | 1.79591 | 32.86   | 1.66666 | 0.833329| 0.000   |
| $\psi$                  | 2   | 0.21457 | 3.93    | 0.20982 | 0.104911| 0.096   |
| $\mu$                   | 2   | 0.04916 | 0.90    | 0.05935 | 0.029676| 0.477   |
| $\alpha$                | 1   | 0.89995 | 16.47   | 0.78944 | 0.789444| 0.000   |
| 2-Way Interactions      | 18  | 1.30371 | 23.85   | 1.31523 | 0.073068| 0.105   |
| $\varphi \times \psi$   | 4   | 0.43450 | 7.95    | 0.45545 | 0.113862| 0.054   |
| $\varphi \times \mu$    | 4   | 0.24801 | 4.54    | 0.23958 | 0.059894| 0.234   |
| $\varphi \times \alpha$ | 2   | 0.16668 | 3.05    | 0.13793 | 0.068966| 0.198   |
| $\psi \times \mu$       | 4   | 0.23067 | 4.22    | 0.23391 | 0.058478| 0.243   |
| $\psi \times \alpha$    | 2   | 0.21038 | 3.85    | 0.15302 | 0.076509| 0.169   |
| $\mu \times \alpha$     | 2   | 0.01347 | 0.25    | 0.00525 | 0.002627| 0.934   |
| 3-Way Interactions      | 12  | 0.62979 | 11.52   | 0.62979 | 0.052483| 0.277   |
| $\varphi \times \psi \times \mu$ | 8 | 0.33862 | 6.20    | 0.34925 | 0.043656| 0.391   |
| $\psi \times \mu \times \alpha$ | 4 | 0.29117 | 5.33    | 0.29117 | 0.072792| 0.162   |
| Error                   | 15  | 0.57264 | 10.48   | 0.57264 | 0.038176|         |
| Total                   | 52  | 5.46572 | 100.00  |         |         |         |

### Table 3

| Source                  | DF  | Seq. SS $\times (10^8)$ | Cont. % | Adj. SS $\times (10^8)$ | Adj. MS $\times (10^8)$ | P-Value |
|-------------------------|-----|-------------------------|---------|-------------------------|-------------------------|---------|
| Model                   | 35  | 5.3576                  | 93.62   | 5.3576                  | 0.1530                  | 0.000   |
| Linear                  | 7   | 3.1786                  | 55.54   | 3.1786                  | 0.4554                  | 0.000   |
| $\varphi$               | 2   | 0.3697                  | 6.46    | 0.4176                  | 0.2088                  | 0.002   |
| $\psi$                  | 2   | 0.9785                  | 17.10   | 1.0253                  | 0.5126                  | 0.000   |
| $\mu$                   | 2   | 0.4183                  | 7.31    | 0.3179                  | 0.1589                  | 0.005   |
| $\alpha$                | 1   | 1.4119                  | 24.67   | 1.4403                  | 1.4403                  | 0.000   |
| 2-Way Interactions      | 16  | 1.3246                  | 23.15   | 1.3001                  | 0.0812                  | 0.005   |
| $\varphi \times \psi$   | 4   | 0.5188                  | 9.07    | 0.5303                  | 0.1325                  | 0.003   |
| $\varphi \times \mu$    | 4   | 0.0216                  | 0.38    | 0.0263                  | 0.0065                  | 0.870   |
| $\varphi \times \alpha$ | 2   | 0.4006                  | 7.00    | 0.3450                  | 0.1725                  | 0.003   |
| $\psi \times \mu$       | 4   | 0.1079                  | 1.89    | 0.1202                  | 0.0300                  | 0.276   |
| $\psi \times \alpha$    | 2   | 0.2755                  | 4.81    | 0.2629                  | 0.1314                  | 0.010   |
| 3-Way Interactions      | 12  | 0.8543                  | 14.93   | 0.8543                  | 0.0711                  | 0.012   |
| $\varphi \times \psi \times \mu$ | 8 | 0.3428                  | 5.99    | 0.3050                  | 0.0381                  | 0.152   |
| $\varphi \times \psi \times \alpha$ | 4 | 0.5114                  | 8.94    | 0.5114                  | 0.1278                  | 0.003   |
| Error                   | 17  | 0.3650                  | 6.38    | 0.3650                  | 0.0214                  |         |
| Total                   | 52  | 5.7227                  | 100.00  |                        |                        |         |
### Table 4

| Source           | DF | Seq. SS × (10^9) | Cont. % | Adj. SS × (10^9) | Adj. MS × (10^9) | P-Value |
|------------------|----|------------------|---------|------------------|------------------|---------|
| Model            | 41 | 1.6309           | 90.76   | 16.3099          | 0.3978           | 0.043   |
| Linear           | 7  | 1.0596           | 58.97   | 10.4282          | 1.4897           | 0.001   |
| $\varphi$        | 2  | 0.2458           | 13.68   | 2.0856           | 0.4042           | 0.011   |
| $\psi$           | 2  | 0.5298           | 29.48   | 4.6753           | 2.3376           | 0.001   |
| $\mu$            | 2  | 0.0455           | 2.53    | 0.4266           | 0.2133           | 0.284   |
| $\alpha$         | 1  | 0.2385           | 13.27   | 2.1242           | 1.0621           | 0.003   |
| 2-Way Interactions | 18 | 0.1514           | 8.43    | 1.5239           | 0.0846           | 0.867   |
| $\varphi \times \psi$ | 4  | 0.0348           | 1.94    | 0.3407           | 0.0851           | 0.694   |
| $\varphi \times \mu$ | 4  | 0.0149           | 0.83    | 0.1558           | 0.0389           | 0.899   |
| $\varphi \times \alpha$ | 2  | 0.0266           | 1.48    | 0.2880           | 0.1440           | 0.415   |
| $\psi \times \mu$ | 4  | 0.0164           | 0.92    | 0.0847           | 0.0211           | 0.964   |
| $\psi \times \alpha$ | 2  | 0.0243           | 1.35    | 0.1644           | 0.0822           | 0.595   |
| $\mu \times \alpha$ | 2  | 0.0342           | 1.91    | 0.3892           | 0.1946           | 0.314   |
| 3-Way Interactions | 16 | 0.4198           | 23.36   | 4.1984           | 0.2624           | 0.178   |
| $\varphi \times \psi \times \mu$ | 8  | 0.1192           | 6.64    | 1.2125           | 0.1515           | 0.483   |
| $\varphi \times \psi \times \alpha$ | 4  | 0.2751           | 15.31   | 2.7602           | 0.6900           | 0.020   |
| $\varphi \times \mu \times \alpha$ | 4  | 0.0254           | 1.41    | 0.2541           | 0.0635           | 0.790   |
| Error            | 11 | 0.1659           | 9.24    | 1.6556           | 0.1508           |         |
| Total            | 52 | 1.7969           | 100.00  |                  |                  |         |

### Table 5

| Source           | DF | Seq. SS | Cont. % | Adj. SS | Adj. MS | P-Value |
|------------------|----|---------|---------|---------|---------|---------|
| Model            | 23 | 0.937030| 95.43   | 0.937030| 0.040740| 0.000   |
| Linear           | 7  | 0.750429| 76.43   | 0.563856| 0.080551| 0.000   |
| $\varphi$        | 2  | 0.573345| 58.39   | 0.478067| 0.029034| 0.000   |
| $\psi$           | 2  | 0.175974| 17.92   | 0.119056| 0.059528| 0.000   |
| $\mu$            | 2  | 0.000951| 0.10    | 0.000260| 0.000130| 0.933   |
| $\alpha$         | 1  | 0.000158| 0.02    | 0.000098| 0.000089| 0.495   |
| 2-Way Interactions | 12 | 0.161890| 16.49   | 0.159905| 0.013325| 0.000   |
| $\varphi \times \psi$ | 4  | 0.113513| 11.56   | 0.091672| 0.022918| 0.000   |
| $\varphi \times \mu$ | 4  | 0.031670| 3.23    | 0.031865| 0.007966| 0.010   |
| $\varphi \times \alpha$ | 2  | 0.012978| 1.32    | 0.016332| 0.008166| 0.024   |
| $\psi \times \alpha$ | 2  | 0.003728| 0.38    | 0.004119| 0.002059| 0.348   |
| 3-Way Interactions | 4  | 0.024712| 2.52    | 0.024712| 0.006178| 0.027   |
| $\varphi \times \psi \times \alpha$ | 4  | 0.024712| 2.52    | 0.024712| 0.006178| 0.027   |
| Error            | 24 | 0.044822| 4.57    | 0.044822| 0.001868|         |
| Total            | 47 | 0.981852| 100.00  |         |         |         |
| Parameter                                      | Optimal value | Responses                  | d   | D   |
|-----------------------------------------------|---------------|----------------------------|-----|-----|
| Friction coefficient between rod and roller ($\mu$) | 0.2           | Required torque (T)        | 0.84|     |
| Die channel angle ($\varphi$)                 | 120°          | Reaction force (F)         | 0.90| 0.85|
| Die outer corner angle ($\psi$)                | 0°            | Warping radius (R)         | 0.92|     |
| Rod bending angle on the roller ($\alpha$)     | 90°           | Equivalent plastic strain (PEEQ) | 0.73|     |