The Optimization Wire Drawing Die Design for Aluminum A1050 and A1070

Jinn-Jong Sheu and Bao-Shan Wang

Department of Mold and Die Engineering, National Kaohsiung University of Science and Technology, No.415, Jiangong Rd., Sanmin Dist., Kaohsiung City 807, Taiwan
Email: jjsheu@nkust.edu.tw

Abstract. Wire drawing is a common used process to reduce the diameter of a small rod or a wire. The parameters of drawing die design such as die angle, bearing length, entrance fillet, and the drawing ratio of each pass are crucial to control the quality of a drawn wire. Taguchi method was adopted to optimize the drawing die geometry design. The lubrication conditions were taken into consideration to observe the effect of friction on the dimension accuracy of the drawn wires. The optimum combination of the drawing die design using 20% of reduction ratio is semi die angle 9 degrees, bearing length 1.2mm and entrance fillet 0.4mm. Two types of aluminum alloy 1070 and 1050 were tested using lubricants sodium sulfide (Na2S), graphite, and drawing oil, respectively. The lubrication effect of sodium sulfide is the best to achieve the lowest drawing load. The lubricant Na2S had the best performance in terms of lowest maximum drawing force for both of A1050 and A1070. The final diameters of the drawn wires were very close to the specification 4.0 mm. The CAE simulations were able to find the optimum design of die. The designed drawing machine was capable of carrying out the experiments and obtains consistent results.

1. Introduction

Drawing process is commonly used to reduce the wire diameter to a required specification for further forming processes or applications. Hsu et al. [1] used Taguchi method to get the optimum drawing wire quality and verified with experimental works. Tai [2] had adopted an L₉(3⁴) orthogonal array of Taguchi method to study the drawing process and found the optimum die designs. Ye [3] had proposed a tube drawing die design method to obtain the optimum surface quality of tubes. The effective strain distribution was used for the cost function of Taguchi method. Fan [4] had used L₂₇(3⁷) orthogonal array for tube drawing die design. The drawing rate is crucial for making a sound tube drawing process. Lin [5] had proposed curved profile drawing die design methods for better tube surface quality and reduced the pass number required.

Shao et al. [6] had carried out titanium alloy wire drawing tests with the lubricants of molybdenum disulphide grease and graphite. The moly grease had the better performance for the drawing process in terms of drawing force. Lee [7] had carried out the stainless wire drawing experiments successfully using the zirconia ceramics drawing die and the lubricants of molybdenum disulphide grease and graphite. Fan [8] had tested the moly grease, the graphite and the butter lubrications for the aluminium ironing process. The graphite lubricant seems had better results. Byonet al. [9] had tested two lubricants for wire drawing and found the powder type lubricant was able to fill the micro cavity of the wire surface and had better lubrication effect. In this paper, Taguchi method was proposed to study the aluminum wire drawing process with lubricants of sodium sulphide (Na₂S), drawing oil (90W-90) and graphite. The drawing loads, wire diameter, and the surface roughness were examined.

2. Drawing pass and drawing die design

2.1. Design of drawing pass
The aluminium wires of A1050, A1070, and A1100 with 5.0 mm diameter were drawn to 4.0 mm. The pass number of drawing was determined considering the reduction rate given in equation 1.

\[ r = \left( \frac{A_0 - A_f}{A_0} \right) \times 100\% \]  

(1)

where \( A_0 \) is the original wire diameter, \( A_f \) is the final wire diameter of each pass. The total reduction rate \( r_t \) of the test is 36%. The required drawing pass number \( n \) was calculated with the assumption of equal reduction rate, \( r \), for each pass and given in equation 2.

\[ r_t = \left[ 1 - \left( 1 - \frac{r}{100} \right)^{\frac{1}{r}} \right] \times 100\% \]  

(2)

Two passes of wire drawing was designed to obtain the better surface quality and prevent the wire broken during the experiment process. The reduction rate calculated was 20% for each pass and the wire diameter for each pass is 4.48, and 4.0mm, respectively.

2.2. Design of drawing die
The geometry and the dimensions of the drawing die designed were shown in Fig. 1 and Table 1, respectively. The approach fillet, \( R \), the die angle, \( \alpha \), the entrance fillet, \( r \), the bearing length, \( L_b \), and the exit angle, \( \beta \), were taken into consideration.

![Figure 1. Dimensions of the drawing die orifice and the bearing length.](image)

| Approach fillet (R) | 5mm |
|--------------------|-----|
| Semi die angle (\( \alpha/2 \)), degrees | 5, 7.5, 9 |
| Entrance fillet (r) | 0, 0.2, 0.4 mm |
| Bearing length (Lb) | 1.0, 1.2, 1.4 mm |
| Relief (\( \beta \)) | 43° |

2.3. Taguchi method
The wire drawing force was adopted for the cost function calculation and the goal of the optimization is the-smaller-the-better. The orthogonal array \( L_9(3^4) \) was adopted for the layout of the experiments. The considered three level design factors \( A, B, \) and \( C \) are the bearing length, \( L_b \), the die angle, \( \alpha \), and the entrance fillet, \( r \), respectively. The experiment layout was given in Table 2. The calculation of the cost function for the-smaller-the better was given in equation 3.

\[ S / N = 10 \log \left( \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right) \]  

(3)

where \( y_i \) is maximum drawing force, \( n \) is the numbers of tests and equal to one for the CAE simulation, the \( S/N \) is the signal to noise ratio.
3. CAE Simulation and the experiment setup

3.1. CAE model
Die drawing die was designed using the CAD software and depicted in Fig. 2. The 3-D geometry of die was input to the CAE software, Deform 3D. The tetrahedral mesh of the A1050 wire was generated in the CAE pre-processor and shown in Fig. 3. The mesh numbers generated initially is 51,000. The Coulomb friction model was adopted and set to 0.08 and 0.12 for excellent and general lubrication of ceramic tools, respectively.

![Figure 2](image2.png)

**Figure 2.** Three dimensional model of the drawing die designed in the CAD system.

![Figure 3](image3.png)

**Figure 3.** Mesh of the wire and the STL geometry of the drawing die.

3.2. Experiment setup of drawing
A wire drawing machine was designed and installed for the experiment tests. The servo motor (60w/110v/60Hz) installed on the wire drawing machine (Fig. 4) was able to stably draw the wire on the drum with a linear speed of 6 mm/s through the die orifice (shown in Fig. 5). The drawing force was measured using data acquisition system and the load cell (capacity 1,200N). The lubricants of sodium sulphide (Na2S), drawing oil and graphite were dropped on the sponge in front of the die orifice.
4. Results and discussion

4.1. Drawing force of the CAE simulation for Al050

The maximum drawing forces for general lubrication of the second pass as well as the S/N ratios for the 9 trials of the Taguchi design were shown in Table 3. The response charts for the different design factors were shown in Fig. 6, Fig. 7, and Fig. 8, respectively. The optimum combination for the drawing die design was bearing length 1.2mm, semi die angle 9 degrees, and the entrance fillet 0.4 mm. The prediction of the drawing force for the best design combination is 41.3Kgf. The prediction loads of the CAE confirmation simulation were 40.8 Kgf for friction coefficient 0.08. The 1% error of the confirmation simulation had verified the optimum design combination is feasible.

Table 3. Drawing force prediction and the S/N ratio for general lubrication condition.

| Try no | Load, Kgf | S/N   |
|--------|-----------|-------|
|        | 1         | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     |
| 1      | 48.4      | 43.2  | 42.0  | 44.0  | 44.4  | 40.8  | 46.4  | 43.2  | 42.4  |
| 2      | -33.7     | -32.7 | -32.5 | -32.9 | -32.9 | -32.2 | -33.3 | -32.7 | -32.5 |
| 3      |           |       |       |       |       |       |       |       |       |
| 4      |           |       |       |       |       |       |       |       |       |
| 5      |           |       |       |       |       |       |       |       |       |
| 6      |           |       |       |       |       |       |       |       |       |
| 7      |           |       |       |       |       |       |       |       |       |
| 8      |           |       |       |       |       |       |       |       |       |
| 9      |           |       |       |       |       |       |       |       |       |

Figure 6. Response chart for the S/N ratio of bearing length.
5. Comparisons of the CAE simulations and the experimental results

5.1. Drawing force
The CAE simulations were carried out only for A1050 but the drawing experiments were tried for A105 and
A1070. The drawing loads of the first and the second passes for the simulation and the experiments were
compared in Fig. 9 and Fig. 10 for different materials. The curves with the labels of ‘0.08’ and ‘0.12’ in Fig. 9
were obtained via the CAE simulation with the friction coefficient 0.08 and 0.12, respectively. The curves
with the label ‘no lubrication’ in Fig. 10 were the experiment results of dry drawing without applying any
lubricants. The drawing force increased dramatically in the beginning and reached a steady state value. The
rank of the performance of the lubricants for both of the drawing passes was Na2S, drawing Oil, and the
graphite in terms of lower drawing force. The maximum drawing force of the experiments of the second pass
for different lubrication were in the range of 31~36Kgf which are close to the CAE prediction with friction
coefficient 0.08.

5.2 Surface roughness and the hardness
The measured maximum drawing forces, surface roughness, and the hardness for A1050, and A1070 were
shown in Table 4, and Table 5, respectively. The maximum drawing forces for the A1050 were in the range of
34 to 40 Kgf for both of the pass one and pass two. The maximum drawing forces for the A1070 were in the
range of 48 to 76 Kgf for both of the pass one and pass two. The maximum drawing loads for the second pass
increased only a small amount that means the strain hardening phenomenon is not significant. The diameters
of the final wire were very close to the specification that shows the drawing processes were successful.

For A1050, the surface roughness of the first and the second passes without lubrication were close to the
surface roughness of die orifice (0.07mm). The performance of the graphite is the better among the three
lubricants in terms of the surface roughness (the drawing loads showed no significant difference). The
hardness measurements of the first and the second passes were changed insignificantly.

For A1070, the surface roughness of the first and the second passes without lubrication were close to the
surface roughness of die orifice (0.07 mm). The performance of the drawing oil is the better among the three
lubricants in terms of the surface roughness and the drawing loads. The measurements of the load and the
hardness for the first and the second passes were changed significantly which indicates the strong effect of strain hardening.

Figure 9. Drawing force of the first pass (left) and the second pass (right) for A1050.

Figure 10. Drawing force of the first pass (left) and the second pass (right) for A1070.

Table 4. The drawing load, wire diameter, surface roughness, and the hardness of A1050 experiment.

| Lubricants       | Load (Kgf) | Wire diameter (mm) | Surface roughness (Ra) | hardness (Hv) |
|------------------|------------|--------------------|------------------------|---------------|
|                  |            |                    |                        |               |
| The first pass   |            |                    |                        |               |
| Deform(0.08)     | 35         | 4.48               | -                      | -             |
| No Lubrication   | 38         | 4.49               | 0.07                   | 29.3          |
| Na2S             | 35         | 4.48               | 0.07                   | 30.9          |
| Drawing Oil      | 34         | 4.48               | 0.17                   | 31.2          |
| Graphite         | 33         | 4.48               | 0.04                   | 28.6          |
| The second pass  |            |                    |                        |               |
| Deform(0.08)     | 35         | 4.0                | -                      | -             |
| No Lubrication   | 40         | 4.01               | 0.05                   | 32.1          |
| Na2S             | 31         | 4.0                | 0.13                   | 31.9          |
| Drawing Oil      | 33         | 4.0                | 0.08                   | 31.8          |
| Graphite         | 34         | 4.0                | 0.04                   | 28.7          |
Table 5. The drawing load, wire diameter, surface roughness, and the hardness of A1070 experiment.

| Lubricants     | Load(Kgf) | Wire diameter(mm) | Surface roughness (Ra) | hardness(Hv) |
|----------------|-----------|-------------------|------------------------|--------------|
| The first pass |           |                   |                        |              |
| No Lubrication | 75        | 4.49              | 0.07                   | 32.1         |
| Na2S           | 35        | 4.48              | 0.07                   | 33.4         |
| Drawing Oil    | 43        | 4.48              | 0.13                   | 30.3         |
| Graphite       | 48        | 4.48              | 0.05                   | 33.3         |
| The second pass|           |                   |                        |              |
| No Lubrication | 76        | 4.01              | 0.1                    | 44.3         |
| Na2S           | 48        | 4.0               | 0.04                   | 39.0         |
| Drawing Oil    | 50        | 4.0               | 0.03                   | 38.0         |
| Graphite       | 58        | 4.0               | 0.17                   | 45.3         |

6. Conclusions
In this research, the Taguchi method was adopted to obtain the optimum drawing die design combination via the CAE simulations for A1050 material. The optimum combination for the drawing die design was bearing length 1.2mm, die angle 18 degrees, and the entrance fillet 0.4 mm. The lubricant Na2S had the best performance in terms of lowest maximum drawing force for both of A1050 and A1070. The final diameters of the drawn wires were very close to the specification 4.0 mm. The CAE simulations were able to find the optimum design of die. The designed drawing machine was capable of carrying out the experiments and obtaining the consistent results.

Acknowledgments
The authors would like to thank the MIRDC for the financial support of the granted project 103-EC-17-A25-1164.

7. References
[1] Q.C. Hsu, Y.D. Jhan, Y.C. Huang, Design and analysis of the circular metal wire drawing process, Forging, Vol. 19, No. 1, pp. 46-53, (2010)
[2] K.C. Tai, M.H. Caleb Li, H.P. Lin, C.F. Chuang, Improving productivity of SUS 304 stainless steel using Taguchi method, Journal of Technology, Vol. 20, No. 4, pp. 333-338, (2005)
[3] S.C. Yeh, Process simulation of cold tube drawing, Master Thesis, Department of Mold and Die Engineering, National Kaohsiung University of Applied Sciences, (2012)
[4] D.T. P., Process and die design of multi-pass cold steel tube drawing, Master Thesis, Department of Mold and Die Engineering, National Kaohsiung University of Applied Sciences, (2011)
[5] S.Y Lin, Process analysis and die design optimization of single-pass cold steel tube drawing, Master Thesis, Department of Mold and Die Engineering, National Kaohsiung University of Applied Sciences, (2011)
[6] S.Y. Shao, C.T. Kwan, W.C. Lee, H.S. Lin, G.Z. Ho, The Process Research of Titanium wire drawing, Forging, Vol. 16, No 4, pp.12-21, (2007)
[7] W.C. Lee, C.T. Kwan, H.R. Shih, An analysis of theory and experiment for stainless wire drawing with zirconia ceramic die, Proceedings of the 24th National Conference on Mechanical Engineering of CSME, No. D01-0012, CSME-P3196-3200, (2007)
[8] C.F. Fang, In Situ observation of grease lubrication in aluminum forming, Master Thesis, Department of Mechanical Engineering National Yunlin University of Science and Technology, (2004)
[9] S.M. Byon, S.J. Lee, D.W. Lee, Y.H. Lee, Y. Lee, Effect of coating material and lubricant on forming force and surface defects in wire drawing process. Transactions of Nonferrous Metals Society of China, Vol. 21, pp. 104-110, Supplement 1, (2011)