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ORIGINAL ARTICLE

Optimization of an aluminum profile extrusion process based on Taguchi's method with S/N analysis

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Abstract Taguchi's design of experiment and numerical simulation were applied in the optimization of an aluminum profile extrusion process. By means of HyperXtrude, the extrusion process was simulated and the effects of process parameters on the uniformity of metal flow and on the extrusion force were investigated with the signal to noise ratio and the analysis of variance. Through analysis, the optimum combination of process parameters for uniform flow velocity distribution was obtained, with the billet diameter of 170 mm, ram speed of 2.2 mm/s, die temperature of 465°C, billet preheated temperature of 480°C, and container temperature of 425°C. Compared with the initial process parameters, the velocity relative difference in the cross-section of extrudate was decreased from 2.81% to 1.39%. In the same way, the optimum process parameters for minimum required extrusion force were gained, with the billet diameter of 165 mm, ram speed of 0.4 mm/s, die temperature of 475°C, billet preheated temperature of 495°C, and container temperature of 445°C. A 24.7% decrease of required extrusion force with optimum process parameters was realized. Through the optimization analysis in this study, the extrusion performance has been greatly improved. Finally, the numerical results were validated by practical experiments, and the comparison showed that the optimization strategy developed in this work could provide the effective guidance for practical production.

Keywords Aluminum profile extrusion · Velocity relative difference · Taguchi's design of experiment · Signal to noise ratio · Analysis of variance

1 Introduction

The aluminum extrusion process is an attractive production method in industry because of its ability to achieve energy and material savings, quality improvement, and development of homogeneous properties throughout the component. Lightweight construction, especially in the area of transportation engineering, is of increasing significance even with decreasing numbers of pieces. But this production technology is quite a lot complicated, and process parameters must be carefully selected so that the desired production quality can be obtained [1–3].

Currently, the selection of process parameters in practice usually is carried out on the basis of experience and corrected after a number of trial extrusion runs before becoming usable. By means of this design pattern, it is difficult to guarantee product quality and productivity when

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the profile structure is complex and actual production has to be stopped or postponed. Computer simulation based on the finite element method or finite volume method is in principle capable of replacing the above trial extrusion runs. It can be used to predict die stresses, temperature distributions, stress and strain gradients of the deforming aluminum, flow velocities, extrusion pressures, dimensions, and distortions, among others. Therefore, a number of research efforts have been made on the numerical simulation of extrusion process, the optimum selection of optimum process parameters and the optimum design of extrusion dies, and great progresses have been made in this field in recent years [4–10].

Choosing the forming energy consumption and the maximization of the possible area reduction as the optimization objectives, Mihelic and Stok applied the finite element discretization and non-linear mathematical programming techniques to optimize the extrusion tools [4]. Ulysse adopted the finite element method combining with optimization techniques to determine the optimal bearing length. The numerical accuracy has been verified using published experimental data for a two-out extrusion die with bearings [5]. Zou presented an improved optimal design method for hot extrusion die using updated sequential quadratic programming method and the results had been validated by real experiment [6]. Byon and Hwang proposed a process with optimal design methodology applicable to cold and hot forming on the basis of an integrated thermo-mechanical finite element process model and a derivative-based optimization scheme. It was demonstrated through their investigation that the approach was effective in revealing the effect of strain-hardening and heat transfer on the predicted optimal die shape in cold and hot extrusion, respectively [7]. Jurkovic et al. put forward two different optimization approaches (classical mathematical and Taguchi's method) relating to determine optimal values of logarithmic strain, die angle, and coefficient of friction with the purpose to find minimal tool loading obtained by cold forward extrusion process [8]. Chen proposed a CAE/CAO model based on finite volume method, artificial neural network, and genetic algorithm to optimize extrusion process parameters and die structure [9]. Lucignano et al. proposed two neural networks to optimize the aluminum extrusion process determining the temperature profile of an Al 6060 alloy at the exit of induction heater and at the exit of the die. Through the comparison with experiments, the temperature profiles, predicted by the neural network, closely agree with experimental values [10].

Nowadays, numerical simulation has been widely used in aluminum extrusion, however, for aluminum profiles extrusion, little systematic study has been carried out on the optimization of process parameters in the literature. Moreover, current research is mostly focused on relatively simple solid or axisymmetric hollow profile. In this paper, Taguchi's design of experiment and computer aided engineering (CAE) simulation will be applied in the optimization of extrusion process of an aluminum hollow profile with complex cross-section. Thirty-two experiments will be employed to evaluate the effects of process parameters (billet diameter, ram speed, billet preheated temperature, die temperature, and container temperature) on velocity relative difference (VRD) and extrusion force. The signal to noise ratio (S/N ratio) is used to find the optimum levels of process parameters, and impact extents of each parameter on VRD and extrusion force will be also investigated by means of the analysis of variance (ANOVA).

2 Experimental works

2.1 Extrusion performance evaluation

In real extrusion process, the uniformity of flow velocity distribution at the die exit greatly influences the quality of the extrudate. Without such a uniform flow control, even simple profiles cannot be extruded successfully. To accurately describe the degree of the velocity uniformity in the cross-section of the extrudate, VRD is introduced in this paper and chosen as an optimization objective for this research:

$$\mathrm{VRD} = \frac{\sum_{i=1}^{n} \frac{|v_i - v_a|}{v_a}}{n} \times 100\% \tag{1}$$

where v_i is the velocity at node i in the cross-section to be researched, v_a is the mean velocity of all nodes for research, and n is the number of nodes to be researched. The smaller the VRD, the better the quality of extruded profile. To gain a more practical velocity distribution, in this paper, 200 nodes in the cross-section are selected and their velocities are recorded.

In addition, too high extrusion load will lead to an intolerable amount of wear in a die, which is the major cause of die failure. Also, extrusion force has a considerable influence on extrudability and environmental load. Thus to minimize, the specific force needed for hot extrusion is significant consideration in press selection. An appropriate prediction or optimization of extrusion force could provide the helpful guideline for choosing the extrusion press in practical production. However, the determination of press requirements for the extrusion of complicated shapes and sections is not straightforward, especially for those with thin walls. Therefore, extrusion force can be considered as another independent optimization objective in this research.

According to practical experience, the more uniform the flow velocity distribution in the cross-section of the extrudate, the better the quality of profile; smaller extrusion force reduces die wear and prolongs the die life. More importantly, an extrusion process with lower energy consumption could be realized.

In this paper, the signal to noise ratio (S/N) with smaller-the-better statistics is applied to find the optimum process parameters, which is defined as follows (noted as η) [11, 12]:

$$\eta = \mathrm{S/N} = -10\log_{10}\left(\frac{1}{m}\sum_{i=1}^{m} y_i^2\right) \tag{2}$$

where y_i is the response value (or objective function value) obtained at the ith experiment, i is the number of experiment, and N is the total number of experiments.

2.2 Process parameters selection and design of experiments

During aluminum profiles extrusion, ram speed, extrusion temperature, and billet diameter (which determined the extrusion ratio) are the most basic and critical process parameters, which have a great impact on the product quality, production efficiency, die life and energy consumption, etc.

Extrusion temperature (including billet preheated temperature, die temperature and container temperature) influences directly the deformation resistance of metal. Usually, higher extrusion temperature softens the metal and is favorable to deform. Thus extrusion force would be decreased with the increasing extrusion temperature.

Ram speed determines the extrusion production efficiency. In a given extrusion die and billet temperature, ram speed (also known as ram speed) is an important parameter affecting temperature distribution in the plastic deformation zone. Under the condition that the extrudate temperature does not exceed the limit for a given alloy, the larger the ram speed, the higher the production efficiency. However, excessive speed can cause overheating of the extrudate as well as tears and other temperature-related surface defects. On the other hand, a low speed can increase the required extrusion force and also decrease tool life because of prolonged contact time between tools and the hot billet. Therefore, an appropriate extrusion or stem speed is essential for hot extrusion [13].

In addition, container diameter (or billet diameter) plays also an important role in the extrusion process. For a given aluminum product, a larger container diameter leads to a higher extrusion ratio, which increases the difficulty in extruding the profile. Moreover, a large velocity difference usually appears in the cross-section of the extrudate because of a higher metal flow near the extrusion center while a slower flow velocity closer to the edge of container due to friction, consequently as many defects such as twist, wave, and bend appear.

In this study, Taguchi's design was carried out to investigate the effect of extrusion parameters on optimization objectives. This is done by selecting an orthogonal array that uses an appropriate number of factors (variables) and levels (values of a particular variable) to be investigated. Through the above analysis, the billet diameter, ram speed, billet preheated temperature, die temperature, and container temperature were chosen as process variables to be optimized. The levels of each parameter are defined on the basis of the design experiences and practical production [13, 14], as shown in Table 1. According to Taguchi's method [15–17], 32 experiments (4^5) are prepared in Table 2.

2.3 Construction of numerical model

2.3.1 UG geometry model

Figure 1 shows the main dimensions and the 3D model of the hollow profile in the present case study. The profile has three cavities, and its wall thickness is 2.8 mm. The section area of the wallboard is 1,179.5 mm^2. Due to its complex structure and high ratio of width to thickness, it belongs to hard-to-deform profiles.

In this work, a porthole die is designed for the production of this profile, which is shown in Fig. 2. A flat porthole die is mainly composed of four parts: an upper die, a lower die, location pins, and coupling bolts. The upper die has portholes, port bridges, and three die mandrels, as illustrated in Fig. 2a. The diameter of upper die is 200 mm

Table 1 Process parameters and their levels

Process parameters	Level 1	Level 2	Level 3	Level 4
A=Billet diameter (mm)	165	170	175	180
B=Ram speed (mm/s)	0.4	1.0	1.6	2.2
C=Die temperature (°C)	445	455	465	475
D=Billet preheated temperature (°C)	450	465	480	495
E=Container temperature (°C)	415	425	435	445

Table 2 Design of experiments with Taguchi's method

Experiment no.	Process parameters				
	A	B	C	D	E
1	1	1	1	1	1
2	1	2	2	2	2
3	1	3	3	3	3
4	1	4	4	4	4
5	2	1	1	2	2
6	2	2	2	1	1
7	2	3	3	4	4
8	2	4	4	3	3
9	3	1	2	3	4
10	3	2	1	4	3
11	3	3	4	1	2
12	3	4	3	2	1
13	4	1	2	4	3
14	4	2	1	3	4
15	4	3	4	2	1
16	4	4	3	1	2
17	1	1	4	1	4
18	1	2	3	2	3
19	1	3	2	3	2
20	1	4	1	4	1
21	2	1	4	2	3
22	2	2	3	1	4
23	2	3	2	4	1
24	2	4	1	3	2
25	3	1	3	3	1
26	3	2	4	4	2
27	3	3	1	1	3
28	3	4	2	2	4
29	4	1	3	4	2
30	4	2	4	3	1
31	4	3	1	2	4
32	4	4	2	1	3

and its height is 70 mm. A porthole is a channel through which material flows into a die orifice. In this case, eight portholes are adopted in the upper die in order to allocate material rationally and balance the metal flow. Die mandrels are used to form the inner contour of a profile. A port bridge is a bracket supporting the die mandrels. Meanwhile drainage channels are applied in die mandrels to guide the material flowing into the ribs which are difficult to form.

The lower die has a welding chamber, a die orifice, and a run-out, as illustrated in Fig. 2b. A welding chamber is used to collect the material flowing through the portholes and weld them into an integral body. The depths of lower die and welding chamber are 70 and 18 mm, respectively. The material in the welding chamber gradually accumulates and the inner hydro-pressure increases until it flows out of the die orifice. Besides, there is a die bearing land in the upper and lower dies, as illustrated in Fig. 2a, b, respectively. The bearing land of the die orifice determines the outer shape and dimensions of the extrudate and adjusts the material flow.

The location pins and coupling bolts are used to couple and fix the upper and lower dies together. For simplification, the thinner parts, such as the bolt holes, which are not relevant with simulation, are omitted in the numerical models. The dies are modeled with 3D modeling software UG and imported to HyperXtrude in IGES or STEP formats.

2.3.2 Mesh generations

To simulate the extrusion process with HyperXtrude, all the domains that material flows through should be extracted and meshed. After importing the 3D models of the extrusion dies into HyperXtrude, it is necessary to manually clean up the tiny entities in the die geometry that influence the size and quality of mesh generating in the following procedure. Being convenient for creating boundary conditions and meshing, the model is divided into five parts: billet, porthole, welding chamber, bearing, and profile. For the sake of simplicity, here portholes and the welding chamber are merged into one part.

In order to control the element number and ensure also calculation accuracy, different element sizes and types at different domains within the whole model are assigned in accordance with the extent of local deformation. In the whole extrusion process, the region near the die bearing undergoes severe shear deformation because the final shape of the profile is formed in the die bearing. Thus, in the regions of bearing and profile, finer triangular prism elements are assigned. While in other regions, relatively coarse tetrahedral elements are used. The meshes of the billet, porthole, welding chamber, and profile are shown in Fig. 3 and the mesh number of the whole model is about 650,000.

2.3.3 Material properties

Constitutive equations are often employed to mathematically determine flow stress as a function of parameters such as strain, strain rate, temperature, and so on. One such constitutive equation used in aluminum profile extrusion, typically referred to as the Sellars–Tegart model, is:

$$\sigma = \frac{1}{\beta}\sinh^{-1}\left(\frac{Z}{A}\right)^{1/n} \tag{3}$$

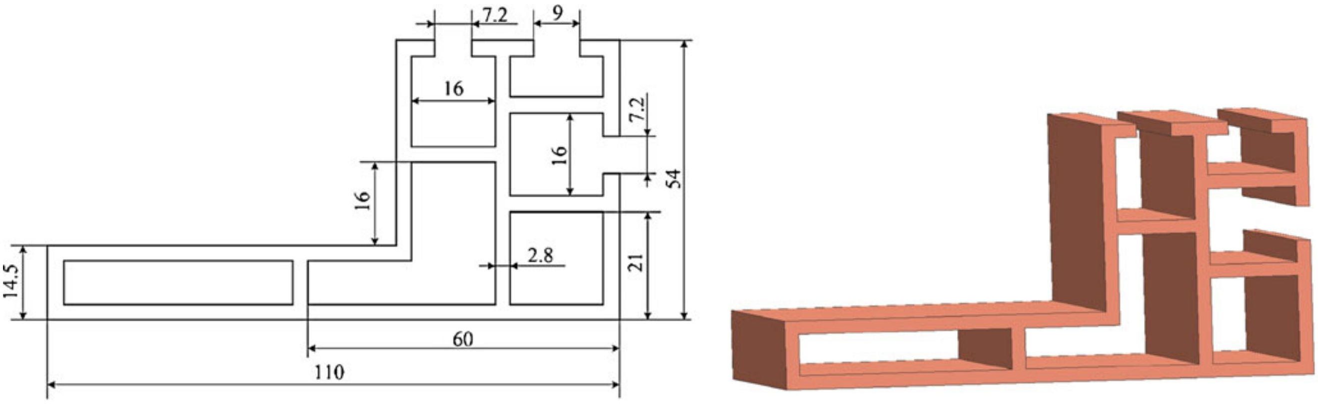


Fig. 1 Geometry and dimensions of the profile in this study

Where σ is the flow stress; β, n, and A are the temperature-independent material parameters; and Z is the Zener–Hollomon parameter, defined by:

$$Z = \dot{\bar{\varepsilon}} e^{Q/RT} \tag{4}$$

Where $\dot{\bar{\varepsilon}}$ is the effective strain rate, Q is the activation energy, R is the universal gas constant, and T is the absolute temperature. Parameter values used for AA6063 in this work are as follows [18]:$Q = 1.416\times\ 10^5 \mathrm{J/mol}$, $R = 8.314 \mathrm{J/(mol \times k)}$, $A = 5.91 \times 10^9 \mathrm{s}^{-1}$, $n = 5.385$, $\beta = 4 \times 10^{-8} \mathrm{m}^2/\mathrm{N}$.

H13 steel is chosen as die material, with good abrasion resistance, hot hardness, and low sensitivity to heat checking, which can be subjected to drastic heating and cooling at high operating temperatures. The mechanical properties of H13 and A6063 are given in Table 3.

2.3.4 Definition of boundary conditions

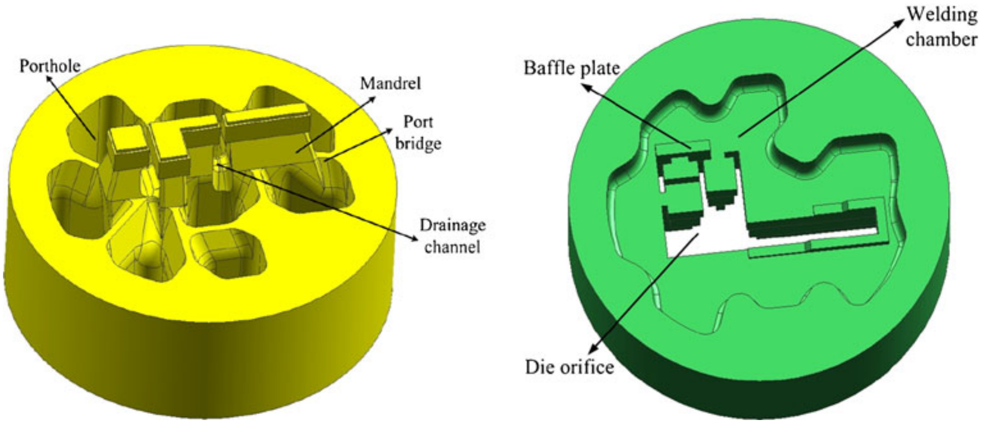
Ideal extrusion process is that required to bring about homogeneous deformation in producing the profile. However, in practice, it is not possible to achieve a situation of ideal or homogeneous deformation in extrusion due to the contributions of inhomogeneous deformation and friction. As a result of strong adhesion of hot aluminum to the extrusion tooling made of tool steel, the friction between the billet and die is strong. For the sake of convenience, the sticking condition is used for all of the interfaces between the billet and the tooling (container and die) except at the die bearing land, where fully slip friction conditions are applied on the surfaces in contact with the bearing. A friction factor of 0.3 was prescribed, so as to simplify the complex interfacial conditions ranging from full sticking at the die entrance to slipping at the end of the bearing [14].

2.3.5 Numerical simulation

To simulate the extrusion process, in the range of process parameters recommended by enterprise, initial process parameters for the simulation (as a reference) are set as follows: billet diameter of 175 mm, ram speed of 1 mm/s, billet preheated temperature of 465°C, die temperature of 455°C, and container temperature of 435°C.

The simulation of the aluminum profile extrusion takes almost 4 h of CPU time on a Linux workstation with 16 GB

Fig. 2 Extrusion dies used for producing the profile



(a) Upperdie (b) Lowerdie

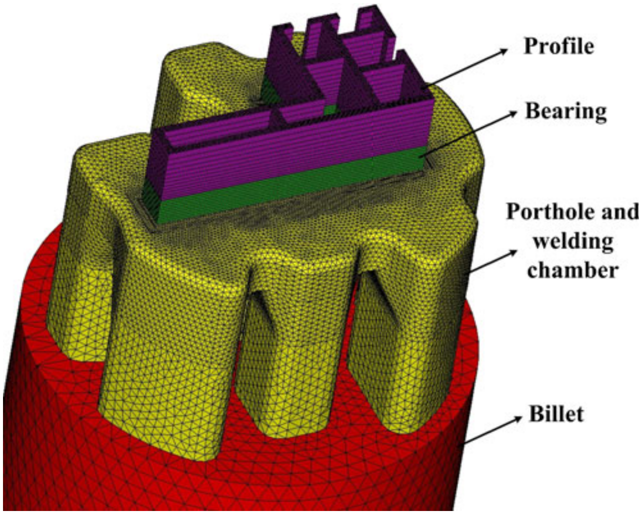


Fig. 3 Mesh generation of CAE model

of RAM and four 3.16 GHz Intel Xeon processors to obtain a stationary solution for the model described above. A large variety of results can be obtained from the numerical simulation, such as velocities, strains, stresses, temperatures, and extrusion forces, etc. The velocity distribution in the cross-section of the extrudate is shown in Fig. 4. It is seen that a relatively lower flow velocity and local twist deformation emerge in the part 1 and part 2, and after calculation, the VRD in this cross-section is 2.81% and the required extrusion force is 1,134 tons, respectively.

3 Results and analysis of experiments

3.1 S/N analysis

The simulations with 32 combinations of process parameters in Table 2 are carried out based on HyperXtrude. With Eq. 1, the S/N ratios for VRD and extrusion force for each simulation are calculated and listed in Table 4.

In order to analyze the influence of each parameter on the VRD and extrusion force, the mean S/N ratio at different levels for each parameter is calculated, as listed in Tables 5 and 6.

The influence of process parameters on S/N of VRD and extrusion force can be also described in Figs. 5 and 6. It is observed that the influences of process parameters on VRD and extrusion force show very different trends.

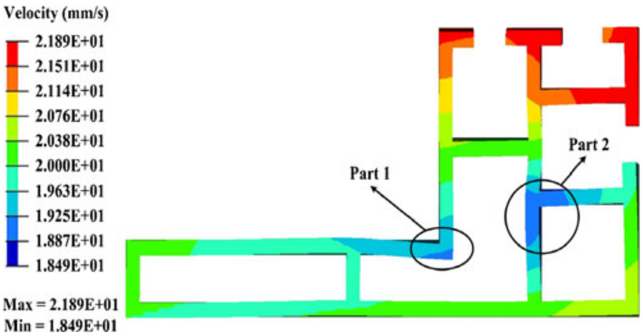


Fig. 4 Velocity distribution in the cross-section of the extrudate with initial process parameters

Based on the above discussion, for the VRD (Fig. 6), the best combination of process parameters was A2B4C3D3E2 (The greater the value of S/N ratio, the better the VRD.), i.e., billet diameter at level 2 (170 mm), ram speed at level 4 (2.2 mm/s), die temperature at level 3 (465°C), billet preheated temperature at level 3 (480°C), and container temperature at level 2 (425°C). With the optimal process parameters, the flow velocity in the cross-section of the extrudate would distribute more evenly. While for the extrusion force (Fig. 7), the minimum required extrusion force was obtained with the optimal combination of A1B1C4D4E4, i.e., billet diameter at level 1 (165 mm), ram speed at level 1 (0.4 mm/s), die temperature at level 4 (475°C), billet preheated temperature at level 4 (495°C), and container temperature at level 4 (445°C).

3.2 Confirmation tests

Once the optimal level of the process parameters has been determined, the next step is to predict and verify the improvement of the performance characteristic using the optimal combination of the process parameters. The estimated *S/N* ratio η_p using the optimal combination can be calculated as [15]:

$$\eta_p = \eta_a + \sum_{v=1}^{q} \left(\overline{\eta}_v - \eta_a \right) \tag{5}$$

Where η_a is the total mean of S/N ratios, $\overline{\eta}_v$ is the mean of the S/N at the optimal level, and q is the number of the process parameters in the optimization model.

Based on Eq. 5, the estimated S/N ratio using the optimal process parameters for minimum VRD can then be calculated,

Table 3 Material properties of AA6063 and H13

Material	Young's modulus [Pa]	Poisson's ratio	Density [Kg·m^3]	Thermal conductivity [N/(s·°C)]	Specify heat [N/(mm^2·°C)]
AA6063	4.0E+10	0.35	2700	198	900
H13	2.1E+11	0.35	7870	24.3	460

Table 4 VRD, extrusion force, and their S/N ratios for different experiments

Experiment no.	VRD (%)	S/N of VRD	Extrusion force (ton)	S/N of extrusion force
1	2.95	30.604	993.3	−59.942
2	2.37	32.505	1,047.1	−60.400
3	2.20	33.152	1,045.9	−60.390
4	2.39	32.431	1,029.1	−60.249
5	2.34	32.623	1,006.6	−60.057
6	2.03	33.833	1,103.5	−60.855
7	1.68	35.494	1,057.5	−60.486
8	1.65	35.650	1,087.6	−60.729
9	2.91	30.722	1,008.4	−60.073
10	3.29	29.648	1,150.1	−60.215
11	2.13	33.427	1,156.6	−61.264
12	2.14	33.391	1,222.4	−61.744
13	2.49	32.060	1,072.1	−60.605
14	2.36	32.542	1,205.3	−61.622
15	2.44	32.258	1,227.4	−61.780
16	1.66	35.604	1,284.2	−62.173
17	2.86	30.884	870.66	−58.797
18	2.34	32.612	1,006.4	−60.055
19	2.19	33.191	1,084.9	−60.708
20	2.79	31.103	1,139.9	−61.137
21	2.75	31.213	904.5	−59.128
22	1.93	34.289	1,033.3	−60.285
23	1.76	35.090	1,127.3	−61.041
24	1.69	35.442	1,169.8	−61.362
25	2.71	31.341	1,012.4	−60.107
26	2.33	32.660	1,076.8	−60.643
27	3.51	29.094	1,218.4	−61.716
28	2.93	30.663	1,194.4	−61.543
29	2.19	33.191	1,050.6	−60.429
30	2.37	32.505	1,159.1	−61.282
31	0.0272	31.309	1,257.9	−61.993
32	0.0188	34.517	1,290.2	−62.213

which is 37.5, and the corresponding VRD is 1.34%. To verify the predicted results, the confirmation experiment was performed using the optimal process parameters by means of HyperXtrude. Figure 7 shows the velocity distribution with the optimum combination of process parameters. After calculation, the VRD with a value of 1.39% is obtained, which has a 5% error between estimated and experimental results. Compared with the initial VRD (2.81%), it is decreased by about 50%, while the required extrusion pressure 1,125.2 tons with this optimal combination.

In the same way, the estimated S/N using the optimal process parameters of A1B1C4D4E4 for minimum extrusion

Table 5 Mean S/N ratios for VRD at different levels

Level	S/N ratio for VRD				
	A	B	C	D	E
1	32.060	31.580	31.546	32.781	32.516
2	34.204	32.574	32.815	32.064	33.580
3	31.361	32.877	33.634	33.068	32.243
4	32.998	33.593	32.628	32.710	32.284

Table 6 Mean S/N ratio for extrusion force at different levels

Level	S/N ratio for extrusion force				
	A	B	C	D	E
1	−60.210	−59.892	−61.130	−60.905	−60.986
2	−60.493	−60.795	−60.930	−60.838	−60.879
3	−61.038	−61.172	−60.708	−60.784	−60.756
4	−61.512	−61.394	−60.484	−60.725	−60.631

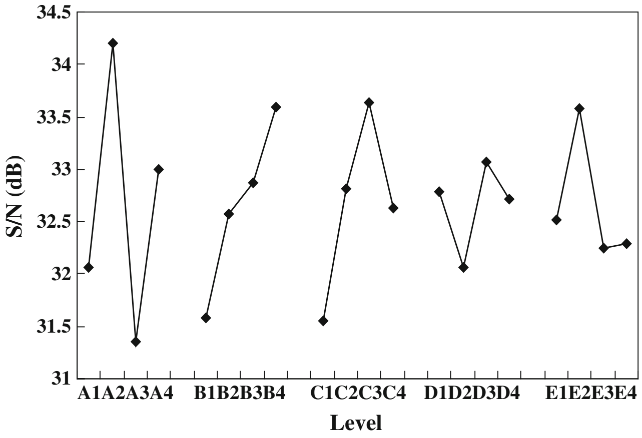


Fig. 5 Plots of S/N for VRD vs. process parameters

force is −58.5 and the corresponding extrusion force is 841.1 tons. Only a 2% difference in extrusion force between estimated and experimental one (856.5 tons) exists. Compared with the initial extrusion force of 1,134 tons, it is decreased by about 24.7%, while the VRD is 2.85% with this optimal combination.

Based on the above analysis, it is shown clearly that there is a good correlation between the estimated and experimental results; furthermore, it is shown clearly that the VRD and extrusion force are greatly improved through this study.

3.3 Analysis of variance

The ANOVA is a set of statistical methods used mainly to compare the means of two or more samples, which can evaluate the impact of various factors on the degree of optimization objectives. Impact extent of each factor could be described by the impact factor. Clearly, the greater the impact factor, the greater influence of this factor on the optimization objective [19, 20].

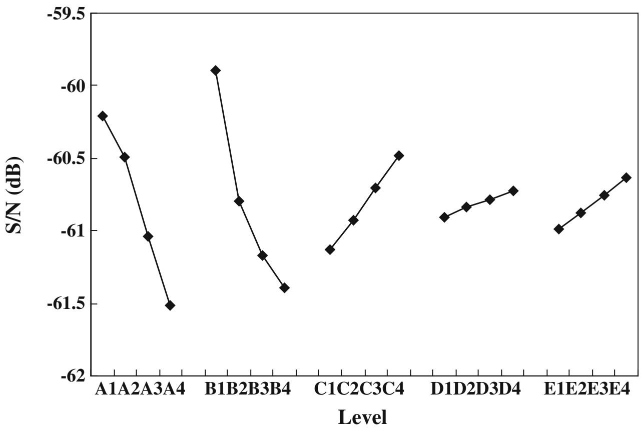


Fig. 6 Plots of S/N for extrusion force vs. process parameters

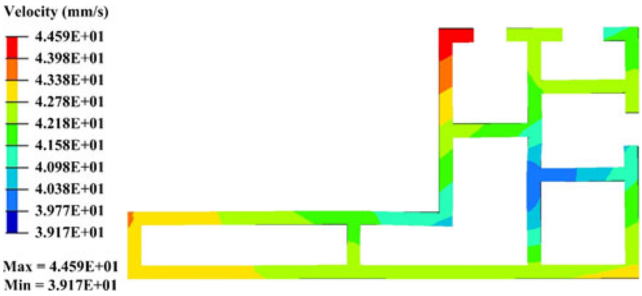


Fig. 7 Velocity distribution in the cross-section of the extrudate with optimum process parameters

By means of ANOVA, the influences of process parameters on VRD and extrusion force were investigated, as listed in Tables 7 and 8. The p value less than 0.05 in Table 7 indicates that the model terms are statistically significant and the effects of the model terms with the p value greater than 0.1 are insignificant. While in Table 8, the results of ANOVA indicate that all model terms are significant. In the following, combining the results in Tables 7 and 8 with practical production, the impact extent of process parameters on VRD and extrusion force will be analyzed.

3.4 Influence of process parameters on VRD

From Table 7, the impact factor of each parameter on VRD could be observed, with the billet diameter being the most significant one, which is 41.9%. In the actual extrusion, the billet diameter is usually 8–15 mm larger than the circumcircle diameter of portholes at the entrance. In this case, with the optimum billet diameter of 170 mm, the minimum VRD is obtained.

To produce a sound profile, the extrudate temperature at the die exit should not exceed the limit extrusion temperature for a given alloy. With analysis in Table 7, the impact factor of the ram speed on the VRD is 19.5%. The research result shows that in the given range of ram speed in this paper, a larger ram speed leads to the more uniform velocity distribution in the cross-section of the extrudate (Fig. 6).

Die temperature and container temperature have significant impacts on the extrusion process, with the factors of 20.58% and 10.91%, respectively. In the extrusion process, material flow in the die cavity mainly depends on the shape of die cavity and friction. Die and container temperatures affect the temperature distribution of deformation metal, which influences the material flow process. Usually in the extrusion process of AA6063, the die temperature is generally taken to be 460°C, while billet temperature is usually 30°C to 40°C higher than the die temperature. Through the analysis for this case, the billet preheated temperature is 480°C, and the optimal die and container

Table 7 Results of ANOVA for VRD

Source	Sum of squares	DOF	Mean square	*F* value	Prob>*F*	Contribution
Model	84.47	15	5.63	9.14	<0.0001	
A	36.22	3	12.07	19.59	<0.0001	41.95%
B	16.84	3	5.61	9.11	0.0009	19.50%
C	17.75	3	5.92	9.60	0.0007	20.58%
D	4.24	3	1.41	2.29	0.1172	4.90%
E	9.42	3	3.14	5.09	0.0115	10.91%
Error	9.86	16	0.62			2.15%
Total	94.33	31				

temperatures are 465°C and 425°C, respectively, which is generally correspondent with practical production.

Billet preheated temperature shows the minimal influence on extrusion process, with a value of only 4.9%. The most appropriate preheating temperature is 480°C, which accords to the practical range of 470°C to 490°C.

3.5 Influence of process parameters on extrusion force

Effect of ram speed on the extrusion force From Table 8, the impact factor of ram speed is 49.78%, so ram speed plays the greatest influence on extrusion force. With the increasing speed of extrusion stem, required extrusion force increases. This is because the larger ram speed causes higher strain rate and greater flow stress. Although the increased plastic deformation heat in the extrusion process will make material soften, it could not compromise the flow stress increase. Therefore, required extrusion force increases with the increasing ram speed.

Effect of billet diameter on the extrusion force Billet diameter shows a relatively significant effect on extrusion force, with the impact factor of 38.01%. Through the analysis, the larger the billet diameter, the greater the extrusion force. This is because with increasing billet diameter the extrusion ratio increases. Thus metal flow resistance increases due to increasing degree of deformation, and the profile is more difficult to form.

Effect of die and container temperatures on extrusion force Die and container temperatures affect to a small extent on extrusion force, two impact factors were both below 10%. With increasing die or container temperature, extrusion force gradually decreases. However, die temperature shows relatively stronger effect than container temperature. This is because simply upsetting deformation in the container occurs, while the shape of profile is formed in die cavity and more intense deformation occurs.

Effect of billet preheated temperature on the extrusion force The effect of billet preheated temperature on the extrusion force is almost negligible, with only 0.26%. In this case, in the temperature range recommended by practical production, material flow stress changes slightly, which maybe explains the minor impact of billet preheated temperature on extrusion force.

Discussion Based on the above analysis, the process parameters showed very different influences on VRD and extrusion force. The optimum combination of process parameters for the best uniform of velocity distribution is not the best one for the least extrusion force, and vice versa. In this paper, the two independent evaluation criteria (VRD and extrusion force) were applied to evaluate extrusion performance. However, extrusion process is a complex one, where there is complicated interaction between process parameters. To more accurately optimize the extrusion

Table 8 Results of ANOVA for extrusion force

Source	Sum of squares	DOF	Mean square	*F* value	Prob>*F*	Contribution
Model	21.14	15	1.41	380.18	<0.0001	
A	8.05	3	2.68	723.47	<0.0001	38.01%
B	10.52	3	3.51	945.80	<0.0001	49.78%
C	1.87	3	0.62	168.03	<0.0001	8.79%
D	0.14	3	0.047	12.70	0.0002	0.67%
E	0.57	3	0.19	50.90	<0.0001	2.69%
Error	0.059	16	0.0037			0.05%
Total	21.20	31				

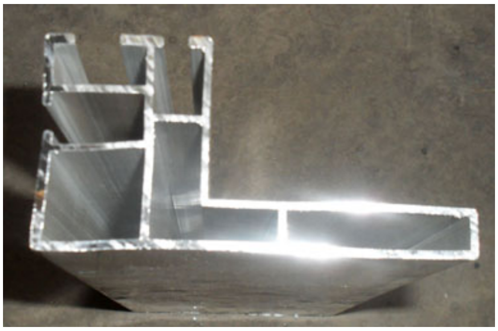


Fig. 8 Aluminum profile produced by experiments with optimum process parameters

process or process parameters, in the following work, a multi-objective function should be considered.

4 Experimental verifications

According to the optimum process parameters for minimum VRD obtained by above procedure, a real mold is manufactured and practical profile extrusion is accomplished. Billet preheated temperature, die temperature, billet diameter, and ram speed were all under close control in order to duplicate the conditions that were applied in the FE simulations. Figure 8 shows the produced profile by experiments according to the optimum process variables for minimum VRD. The figure shows that the velocity distribution at die exit has similar trend as the numerical result (Fig. 7), and slight twist deformation occurs in the bottom of the profile with relative low velocity. Therefore, the optimization strategy developed in this research could provide reasonable results and useful guidelines for practical production.

5 Conclusions

In this paper, based on Taguchi's design of experiments, 32 combinations of process parameters have been made to simulate the extrusion process for a hollow aluminum profile with HyperXtrude. S/N ratio analysis and ANOVA were used to investigate the influence of process parameters (including billet diameter, ram speed, billet preheated temperature, die temperature, and container temperature) on VRD and extrusion force. The following conclusions were drawn:

(1) Based on ANOVA, the extent of the impact of process parameters on VRD has been obtained and the results of the analysis showed that billet diameter (or extrusion ratio) had the greatest influence, followed by die temperature, ram speed and container temperature, and billet preheated temperature affected slightly. The above conclusion was very accordant to practical observation. By means of S/N analysis, the optimum combination of process parameters for minimum VRD was obtained, i.e., billet diameter of 170 mm, ram speed of 2.2 mm/s, die temperature of 465°C, billet preheated temperature of 480°C, and container temperature of 425°C. Compared with VRD on the initial process parameters, VRD is decreased by 50% after optimization.

(2) In the same way, the extent of the impact of process parameters on extrusion force has been analyzed. With billet diameter of 165 mm, ram speed of 0.4 mm/s, die temperature of 475°C, billet preheated temperature of 495°C, and container temperature of 445°C, the minimum required extrusion force was obtained. The extrusion force after optimization is decreased by 24.7% in comparison with that in the initial scheme.

(3) Through CAE simulation with optimum combinations of process parameters, the optimization strategy proposed in this paper was verified by experiments, which could give useful guidelines for practical production of aluminum profile extrusion.

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