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# Mathematical model of determination of die bearing length in design of aluminum profile extrusion die[①]

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**Abstract:** Based on the finite element simulation of profile extrusion process, the effect of local extrusion ratio, die bearing area and the distance between extrusion cylindrical center and local die orfice center on mental flow velocity was investigated. The laws of deformed metal flow on profile extrusion process were obtained. The smaller the local extrusion ratio, the faster the metal flow velocity; the smaller the area of die bearing, the faster the metal flow velocity; the smaller the distance of position of local die orifice(the closer the distance of position of local die orifice from extrusion cylindrical axis), the faster the metal flow velocity. The effect of main parameters of die structure on metal flow velocity was integrated and the mathematical model of determination of die bearing length in design of aluminum profile extrusion die was proposed. The calculated results with proposed model were well compared with the experimental results. The proposed model can be applied to determine die bearing length in design of aluminum profile extrusion die.

**Key words:** profile extrusion; finite element simulation; mathematical model; die bearing length
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## 1 INTRODUCTION

During the profile extrusion process, the determination of die bearing length is one of the most important parameters in design of extrusion die, which affect directly the dimension tolerance, surface quality and geometrical shape of the extruded workpiece. Once the die bearing length is chosen improperly, the non-balanced metal flow velocity from die orifice is induced, resulting in cracking, bending, distorting and twisting on the extruded profile, or damage to the dies[1-3]. The method to design the die bearing length mainly depends on the evolutional form on the formula of extrusion force with its even pressure distributed[4]. Because the effect of position of die orifice on metal flow is not considered, the metal flow is not balanced well with the above design method.

With the rapid development of computer technology and finite element method, it is stressed to build a mathematical model of metal plastic forming process with plastic finite element method[5-12]. Based on the ANSYS software and APDL programing technology, the effect of local extrusion ratio, die bearing area and the distance between the extrusion cylindrical center and the die orifice center on mental flow velocity is investigated in this paper. Based on the laws of deformed metal flow obtained on profile extrusion process, the effect of main parameters of die structure on metal flow velocity is integrated and the mathematical model of determination of die bearing length in design of aluminum profile extrusion die is proposed.

## 2 LAWS OF DEFORMED METAL FLOW IN PROFILE EXTRUSION PROCESS[13]

### 2.1 Effect of local extrusion ratio on metal flow velocity

In order to reflect the effect of extruded force on metal flow velocity, the local extrusion ratio, $\lambda_i$, is defined as the ratio of area of extrusion cylinder to area of local die orifice,

$$\lambda_i = F/F_i \quad (1)$$

where $F$ is the cross sectional area of extrusion cylinder, $F_i$ is the cross sectional area of local die orifice.

Three die orifices with different circular diameters(8, 12, 16 mm) are distributed equidistantly along the direction of transverse axis as shown in Fig. 1 and Fig. 2. Based on the FE simulations of extrusion processes shown in Fig. 3 and Fig. 4, the extruded length from the die orifice with diameter of 16 mm is

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longer than that from the die orifice with diameter of 12 mm, the extruded length from the die orifice with diameter of 12 mm is longer than that from die orifice with diameter of 8 mm (see Fig. 5). The smaller the local extrusion ratio, the faster the metal flow velocity.

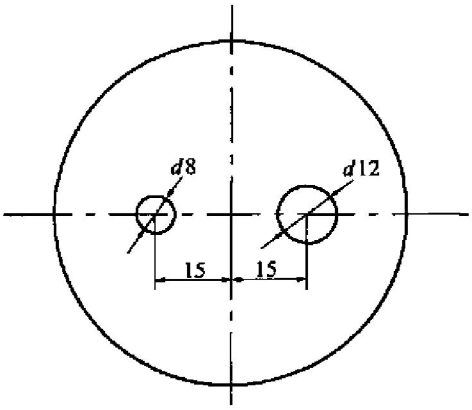


**Fig. 1** Die layout of extrusion test 1 (Unit: mm)

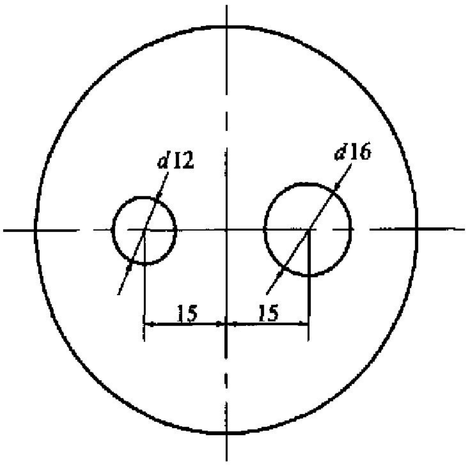


**Fig. 2** Die layout of extrusion test 2 (Unit: mm)

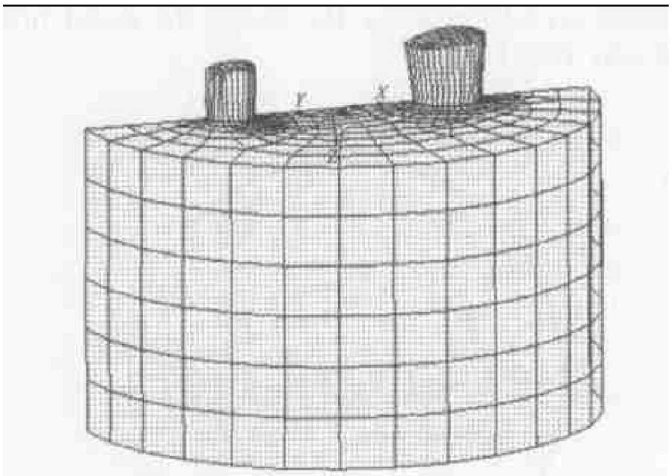

**Fig. 3** Finite element simulation of extrusion test 1

## 2.2 Effect of die bearing area on metal flow velocity

In order to explain the effect of frictional force

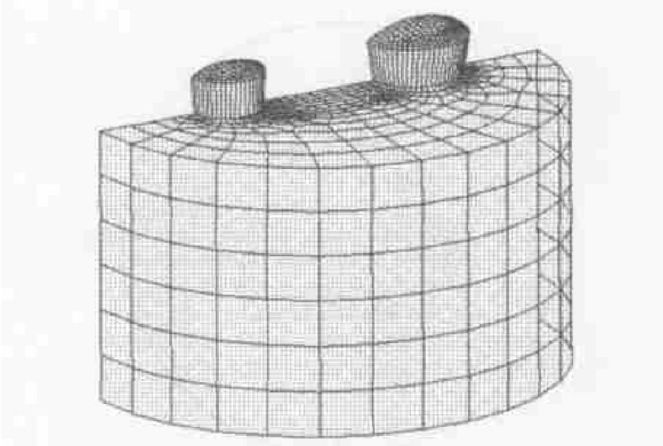

**Fig. 4** Finite element simulation of extrusion test 2

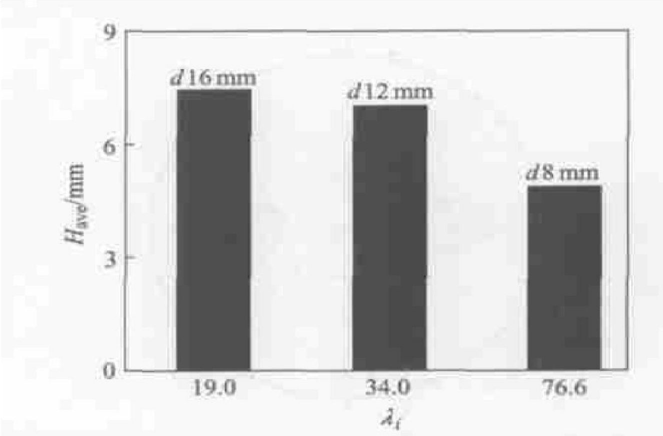


**Fig. 5** Relationship between local extrusion ratio $\lambda_i$ and extruded workpiece height

on metal flow velocity, the die bearing area is defined as the product of perimeter of local die orifice and local die bearing length:

$$A_i = C_i \times L_i \quad (2)$$

where $A_i$ is the area of local die bearing, $C_i$ is the perimeter of local die orifice and $L_i$ is the local die bearing length.

The circular, hexagonal and triagonal die orifices with different perimeters, the equal distance (15 mm) from extrusion center, the equal cross-sectional area and die bearing length are shown in Fig. 6 and Fig. 7. Based on the FE simulations of extrusion processes shown in Fig. 8 and Fig. 9, the extruded length from circular die orifice is longer than that of hexagonal die orifice, the extruded length from hexagonal die orifice is longer than that from triagonal die orifice (see Fig. 10). The perimeter of circular die orifice is the shortest, and that of hexagonal one is the shorter, that of triagonal one is the longest among of them. In other words, the area of die bearing of circular die orifice is smaller than that of hexagonal one, which is smaller than that of triagonal one. These show that the smaller the area of die bearing, the faster the metal flow velocity.

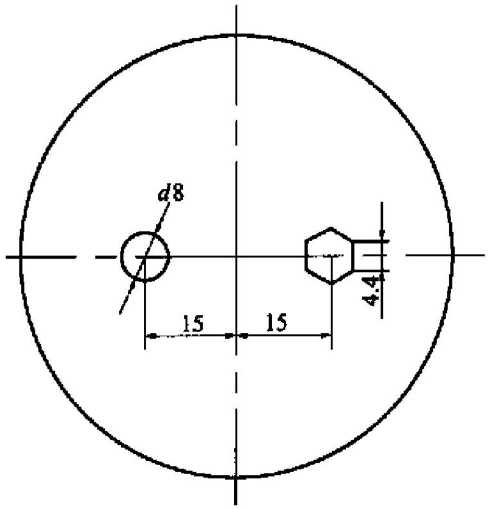


**Fig. 6** Die layout of extrusion test 3 (Unit: mm)

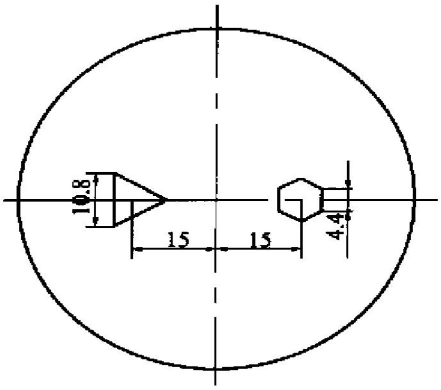


**Fig. 7** Die layout of extrusion test 4(Unit: mm)

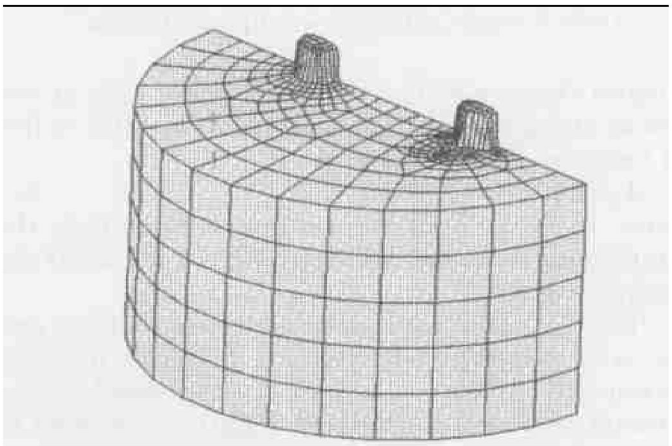

**Fig. 8** Finite element simulation of extrusion test 3

## 2.3 Effect of position of die orifice on metal flow velocity

In order to illustrate the effect of the relative distance between the extrusion cylindrical axis and the position of local die orifice on metal flow velocity, the above relative distance is defined as the distance of die orifice($r_i$). There are five small circular die orifices with equal diameter and distance between ones, distributed along the direction of transverse axis as shown in Fig. 11. Based on the FE simulation of extrusion process shown in Fig. 12, the farther the distance of position of local die orifice from extrusion cylindrical axis, the shorter the length of extruded workpiece. The closer the distance of position of local die orifice from the extrusion cylindrical axis, the faster the metal flow velocity (see Fig. 13).

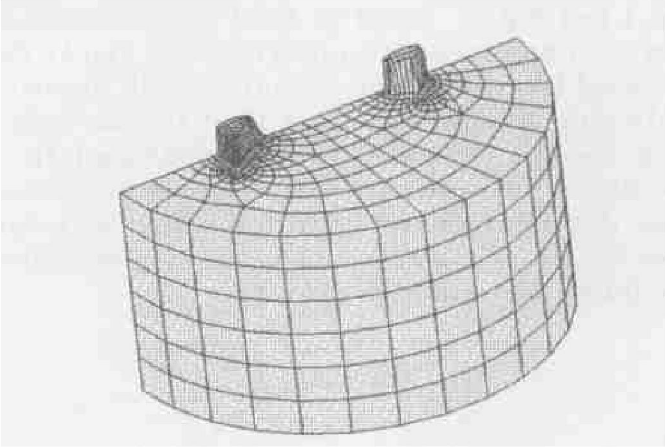

**Fig. 9** Finite element simulation of extrusion test 4

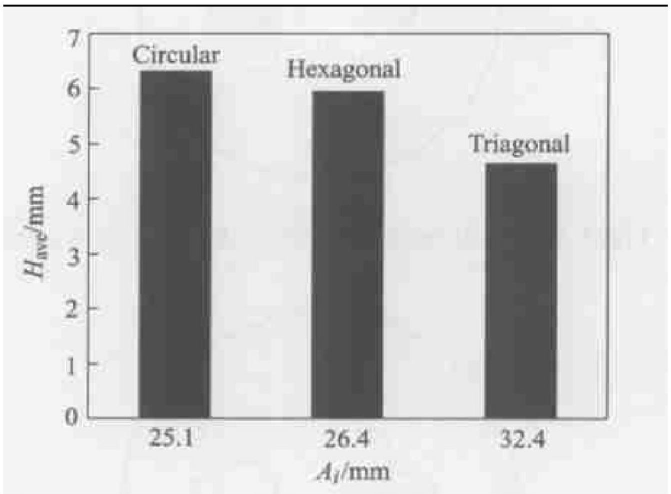


**Fig. 10** Relationship between die bearing area $A_i$ and extruded workpiece height

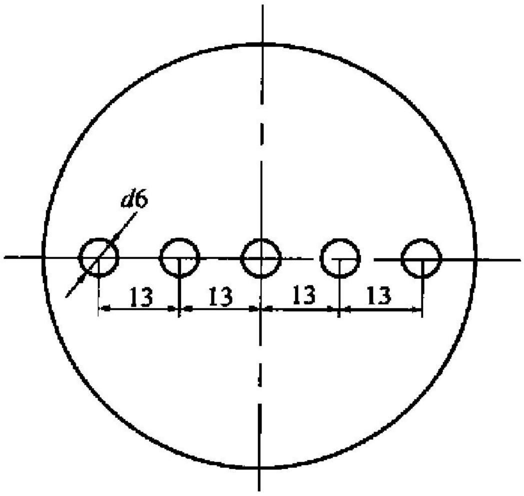


**Fig. 11** Die layout of extrusion test 5(Unit: mm)

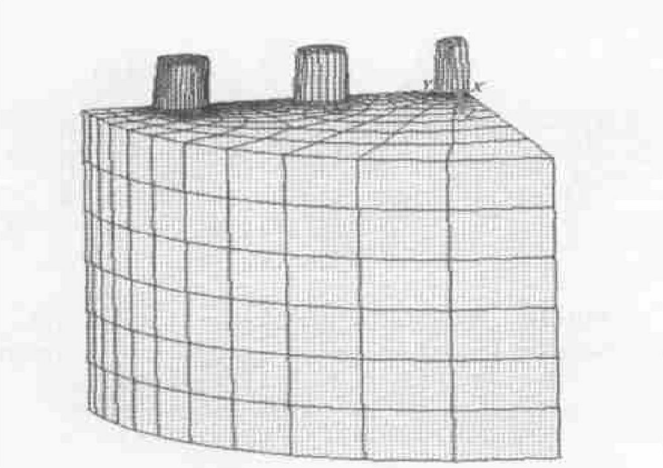

**Fig. 12** Finite element simulation of extrusion test 5

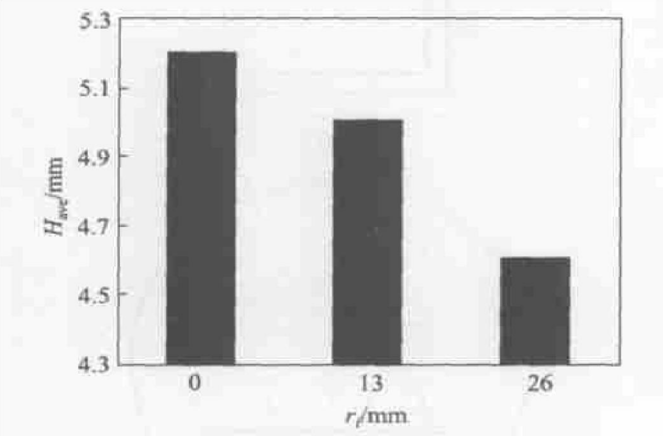


**Fig. 13** Relationship between die hole distance $r_i$ and extruded workpiece height

## 3 GENERAL FORMULA OF DESIGN OF DIE BEARING LENGTH[14]

### 3.1 Effect of important die structural parameters on metal flow velocity

Based on the above simulation analysis, the laws of effect of important die structural parameters on metal flow velocity are gained as follows.

1) The smaller the local extrusion ratio ( $\lambda_i$), the faster the metal flow velocity( $v_i$);

2) The smaller the area of die bearing ( $A_i$), the faster the metal flow velocity ( $v_i$);

3) The smaller the distance of position of die orifice $r_i$( the closer the distance of position of die orifice from extrusion cylindrical axis), the faster the metal flow velocity $v_i$.

### 3.2 Construction of mathematical model of determination of die bearing length

Following the above laws of deformed metal flow, the metal flow velocity $v_i$ is considered as the function of local extrusion ratio $\lambda_i$, die bearing area $A_i$ and the distance of position of local die orifice $r_i$. It is expressed by

$$v_i = f(\lambda_i,\ A_i,\ r_i) \tag{3}$$

The function $f$ is assumed as

$$v_i = k \frac{1}{\lambda_i^{n_1}} \frac{1}{\lambda_i^{n_2}} \frac{1}{\lambda_i^{n_3}} \tag{4}$$

And $n_1 > 0$, $n_2 > 0$, $n_3 > 0$. From a lot of practical trials, $n_1 = 1$, $n_2 = 1$, $n_3 = 1/3$, Eq. (4) is changed as

$$v_i = k \frac{F_i}{F} \frac{1}{C_i \cdot L_i} \frac{1}{r_i^{1/3}} \tag{5}$$

where $v_i$ is the metal flow velocity of $i$th element of die orifice, $k$ is the proportional coefficient, $L_i$ is the die bearing length of $i$th element of die orifice, $C_i$ is the perimeter of $i$th element of die orifice, $r_i$ is the distance between $i$th element of die orifice and extrusion cylindrical axis, $F$ is the cross-sectional area of extrusion cylinder, $F_i$ is the cross-sectional area of the local die orifice.

Choosing the benchmark element and assuming its die bearing length as $L_0$, the metal flow velocity of benchmark element is followed as

$$v_0 = k \frac{F_0}{F} \frac{1}{C_0 \cdot L_0} \frac{1}{r_0^{1/3}} \tag{6}$$

Combining Eq. (5) and (6),

$$\frac{v_i}{v_0} = \frac{F_i C_0 L_0 r_0^{1/3}}{F_0 C_i L_i r_i^{1/3}} \tag{7}$$

The condition of balanced metal flow of extruded workpiece is satisfied by

$$\frac{v_i}{v_0} = 1 \tag{8}$$

Thus

$$L_i = \frac{F_i C_0 L_0 r_0^{1/3}}{F_0 C_i r_i^{1/3}} \tag{9}$$

### 3.3 Procedure of design of die bearing length

1) The cross section area of complex profile extrusion workpiece is divided into a number of simple elements of die orifice.

2) Calculate areas of every elements of die orifice.

3) Calculate perimeters of every elements contacted with die bearing.

4) Calculate distances of every elements from its mass center to extrusion cylindrical axis.

5) The die bearing length of the furthest element from extrusion cylindrical axis with minimum opening of die orifice (5th element in Fig. 14) is first given, the minimum die bearing length $L_0$ is generally given as 2 − 5 mm. Then the die bearing lengths of every elements are calculated by Eq. (9).

6) The break parts between die bearing lengths are replaced with the slope lines.

In some special situations, Eq. (9) may be modified as following[4].

1) The die bearing length is added properly with

1 mm on the screw part of profile.

2) The die bearing length is increased properly by 1 mm on the rounded part of transition of two sides of profile.

3) The die bearing length is decreased by 1 mm on the end part of profile where metal flow is blocked in three directions.

4) The die bearing length is increased properly by 1 mm on the round end part of profile.

When the die bearing length is increased by 8 - 15 mm, the more length of die bearing is not used to block metal flow because the cooled and shrinked metal is separated from contact of die bearing. The blocked angle is also applied on importing part of die orifice to adjust metal flow[4].

## 4 CALCULATION EXAMPLE

The cross section diagram of selected practice profile in Ref. [15] is shown as Fig. 14. The half of part is divided to six elements shown in Fig. 14, $F_i$, $C_i$ and $r$ are calculated and listed in Table 1 based on Eq. (9), where $L_1 = 3$ mm.

**Table 1** Calculation of die bearing length in design of aluminum profile extrusion die

| Element | $F_i$/mm$^2$ | $C_i$/mm | $r_i$/mm | $L_i$/mm | $L_i$/mm[15] |
|---|---|---|---|---|---|
| 1th | 13.43 | 11.43 | 46.87 | 3.00[1)] | 3.00 |
| 2th | 23.52 | 23.45 | 46.00 | 2.57 | 2.61 |
| 3th | 8.40 | 8.40 | 46.00 | 2.57 | 2.61 |
| 4th | 40.00 | 29.66 | 36.67 | 3.74 | 4.08 |
| 5th | 107.00 | 63.07 | 16.50 | 6.14 | 6.22 |
| 6th | 90.00 | 20.00 | 4.72 | 24.67[2)] | 14.11 |

1) $L_1$ is increased by 1 mm on round end where $L_1 = 4$ mm;
2) $L_6$ is exceeded with 8 - 15 mm where $L_6 = 15$ mm.

The results of calculation by Eq. (9) agree well with the experimental results in Ref. [15].

The cross section diagram of selected angle profile in aluminium factory is shown in Fig. 15. In order to verify further the correctness of the mathematical model of design of die bearing length derived in this paper, Eq. (9) is used to determine the die bearing length in design of angle aluminum profile extrusion die. The cross section is divided into five elements as shown in Fig. 15, $F_i$, $C_i$ and $r$ are calculated and listed in Table 2, where $L_5 = 4$ mm.

Based on the calculated results (see Table 2) of die bearing length, the angle aluminum die (see Fig. 16) is designed, manufactured and applied to produce successfully extruded workpieces which have finished surfaces and corrected dimensions (see Fig. 17).

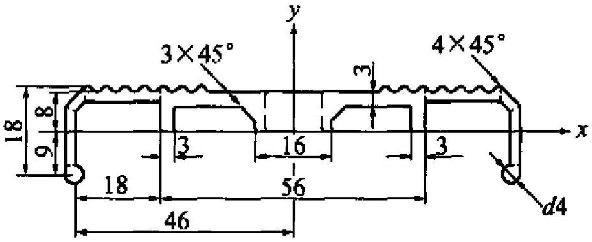


**Fig. 14** Schematic diagram of calculating die bearing length in actual example (Unit: mm)
(The half of part is divided into six elements where the round part is 1th element and the lines of partition are broken lines)

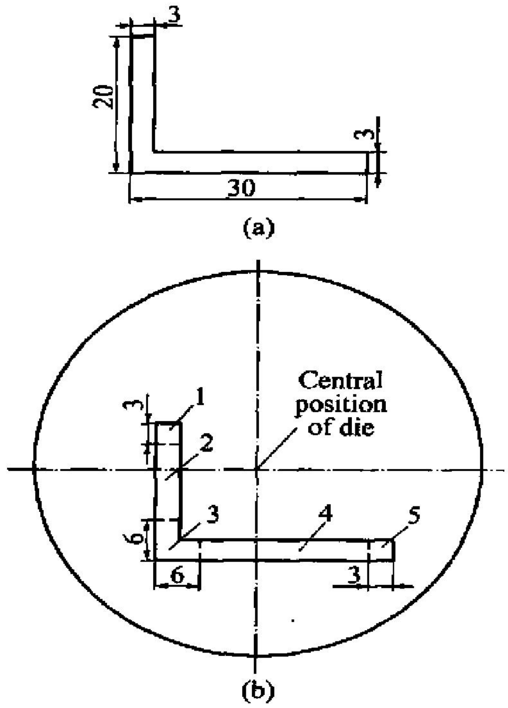


**Fig. 15** Schematic diagram of calculating die bearing length in design of aluminum profile extrusion die (Unit: mm)
(a) —Section diagram of angle profile;
(b) —Calculating diagram of die bearing length

**Fig. 16** Angle aluminum die

**Table 2** Calculation of die bearing length in design of angle aluminum profile extrusion die

| Element | $F_i$/ mm$^2$ | $C_i$/ mm | $r_i$/ mm | $L_i$/ mm |
|---|---|---|---|---|
| 1th | 9 | 9 | 22.19 | 4.4$^{1)}$ |
| 2th | 33 | 22 | 26.45 | 6.2 |
| 3 th | 27 | 18 | 32.75 | 5.8 |
| 4 th | 63 | 42 | 28.59 | 6.1 |
| 5 th | 9 | 9 | 29.38 | 4.0$^{2)}$ |

1) $L_1$ is decreased by 1 mm on the end part where $L_1$= 3.4 mm;
2) $L_5$ is decreased by 1 mm on the end part where $L_5$= 3 mm

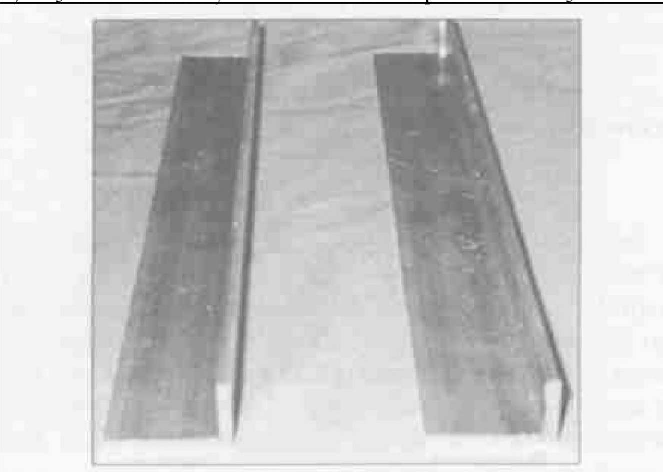

**Fig. 17** Extruded products photo

## 5 CONCLUSION

The laws of deformed metal flow in the profile extrusion process have been obtained by FEM simulation technique. The smaller the local extrusion ratio, the faster the metal flow velocity. The smaller the area of die bearing, the faster the metal flow velocity. The smaller the distance of position of local die orifice (the closer the distance of position of local die orifice from extrusion cylindrical axis), the faster the metal flow velocity. The effect of main parameters of die structure designed on metal flow velocity has been integrated. The mathematical model of determination of die bearing length in design of aluminum profile extrusion die has been constructed. The calculated results with proposed model were well compared with the experimental results. The proposed model can be applied to determine die bearing length in design of aluminum profile extrusion die.

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