Process analysis in mandrel extrusion of special-shaped aluminum alloys profile

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Abstract

In order to reveal abnormal shaped aluminum alloy law of needle piercing extrusion formation, setting the missile empennage as an example, this paper adopts the non-linear finite element to conduct the three-dimensional thermal simulation of abnormal shaped material law of needle piercing extrusion formation process and analyses systematically the influence of process law on temperature change, additional tensile stress and forming load. The results show that, in the range of low-speed extrusion, the billet's highest peak temperature shows a decreasing trend, and with the extrusion speed increasing, the decrease of highest peak temperature decreases, while the axial extra tensile stress on the mouth of model increases accordingly; the axis part of the mold's mouth is a high-temperature zone in the forming process, and with the axis center distance increasing, the temperature decreases gradually; and with the pressing reduction's increase, the gradient of temperature decreasing trend slows down gradually. This provides a theoretical basis to technical design of abnormal shaped material needle piercing extrusion formation and the metal distortion flow control.

K e y   w o r d s: mandrel extrusion, aluminum alloys profile, coupled thermal-mechanical numerical simulation

1. Introduction

Lightweight material and structure are important long-term goals and development trend that the aerospace and other areas attempt to achieve [1]. Super-hard aluminum alloy, titanium alloy and other lightweight materials, which have been widely used, are precisely and continuously developed in response to this demand [2]. Because of their poor plasticity, extrusion process is often used. However, the complexity of technology makes it difficult to achieve control of the metal flow and the quality in the deformation [3]. With development of computer technology, we can combine the finite element simulation and plastic theory to control the distribution of stress field and temperature field which can improve metal flow behavior

[4] radically in the forming process and avoid the occurrence of defects [5]. Therefore the purpose of optimizing the technological parameters and the die design [6] to extrude metal can be achieved easily [7], which is also an effective way to improve the products quality and the mechanical properties.

The present research is mostly limited to the hollow abnormal cross-sectional material which is produced through division mold extrusion. In contrast, needle piercing extrusion is easier to improve hollow seamless overall performance of extruded products. But the corresponding researches are seldom reported. For the above shortcomings, this paper sets the typical cross-sectional extrusion material which is used to produce missile's empennage as an example, and analyzes the forming law deeply.

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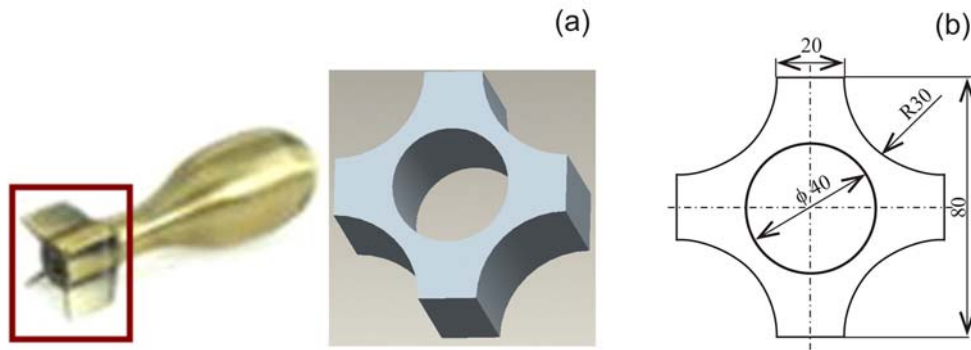
Fig. 1. Cross section of the extrudate with the shaded area selected for simulation (guided missile): (a) the missile's empennage, (b) the size's sketch map.

T a b l e 1. Physical properties of the workpiece and tooling and heat transfer coefficients

Physical properties	AA7075	H13 steel
Heat capacity (N mm^{-2} ℃$^{-1}$)	2.39	5.6
Thermal conductivity (W m^{-1} ℃$^{-1}$)	130	28.4
Emissivity	0.1	0.7
Heat transfer coefficient between tooling and workpiece (N ℃$^{-1}$ s^{-1} mm^{-2})	11	11
Heat transfer coefficient between tooling/workpiece and air (N ℃$^{-1}$ s^{-1} mm^{-2})	0.02	0.02

2. Research program

2.1. Process analysis

Empennage is one of the important parts of the missile that determines the missile's flight path stability and whether the missile can hit the target or not. The size and structure of a missile are shown in Fig. 1.

In order to achieve lightweight design and meet the overall requirements of the structure and performance, super-hard alloy needle piercing hot extrusion is often used to produce it.

2.2. Finite element model

The extrusion process was simulated through finite element software DEFORM^{TM}-3D, and it adopts isoparametric elements such as four-node tetrahedral to disperse the workpiece. Taking the overall symmetry into consideration, and at the same time to reduce cell quantity and improve the computation speed, 1/4 of the workpiece is chosen to simulate, restrictions are imposed on the point of the symmetry plane and the normal speed along the symmetry plane is 0, finite element model is shown in Fig. 2.

In order to improve the accuracy and convergence of computing, according to the part geometry, local refinement is used to create griddings at the transition and large deformation regions. The number of work-
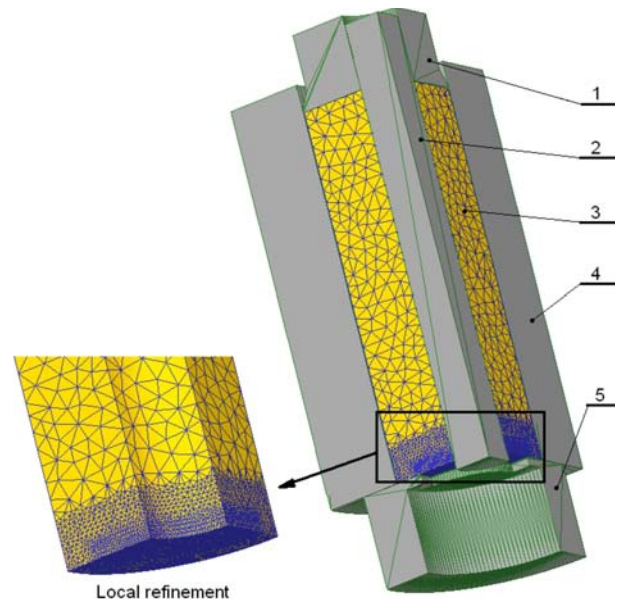

Fig. 2. Finite element model and local refinement (1 – stem, 2 – mandrel, 3 – workpiece, 4 – container, 5 – die).

piece nodes and units are 5188 and 21839, respectively.

2.3. Research program

The super-hard aluminum alloy 7075 blank of a length of 200 mm and the internal and external dia-

meter of 40.5 ± 0.10 mm and 110 ± 0.10 mm, is chosen to do the research. Material property is rigid (sticky) plastic model and the mold's material is the H13 steel. The thermal object parameters of blank and tools are shown in Table 1 [8]. The forming speed is $2\,\mathrm{mm\,s^{-1}}$ and the initial forming temperature is 430 °C. Constant shear friction model is used, and the corresponding friction factor is 0.4, which is tested through the annular hot compression test.

3. Discussion and analysis

3.1. Process optimization

The extrusion process is so complex that the extrusion speed, forming temperature and mold structure all have important impacts on it. To facilitate the study, we fix other process parameters and only take forming speed's influence on the extrusion process as an example to optimize and determine technological parameters. The comparison of different extrusion speed influence on the extrusion process is shown in Fig. 3.

As can be seen in Fig. 3a, with the extrusion process continuing, the maximum temperature of the blank shows a decreasing trend and the maximum temperature decreases significantly as the extrusion speed decreases. When the extrusion speed reduces from $5\,\mathrm{mm\,s^{-1}}$ to $1\,\mathrm{mm\,s^{-1}}$, the highest temperature rate of decline can reach about 10 %.

When the metal flows through the extrusion die opening, because of the friction's effect, its flow speed's heterogeneity is more significant. When the heterogeneity reaches a certain value, an additional stress can cause surface crack. When the amount of punch compression reaches 20 mm, a contrast of the axial stress at the die opening under different extrusion speed is made, which is shown in Fig. 3b. From the figure we can see that when the extrusion speed is $1\,\mathrm{mm\,s^{-1}}$ or $3\,\mathrm{mm\,s^{-1}}$, with the extrusion process continuing, the axial additional tensile stresses in the die pocket all show a trend that they increase first and decrease later as the extrusion process continues; when the extrusion speed is $3\,\mathrm{mm\,s^{-1}}$, the axial additional stress is slightly higher than the former in entirety. When the extrusion speed increases to $5\,\mathrm{mm\,s^{-1}}$, the axial additional tensile stresses in the die pocket increase significantly, and its peak value reaches 25.8 MPa due to its increase all the time in the extrusion process, thus increases the product's possibility of surface crack.

As is known from the comparison of the extrusion load change, which is shown in Fig. 3c, when the extrusion speed is $1\,\mathrm{mm\,s^{-1}}$ or $3\,\mathrm{mm\,s^{-1}}$, the peak value of the extrusion load fluctuates around 400 kN; when the extrusion speed increases to $5\,\mathrm{mm\,s^{-1}}$, the peak
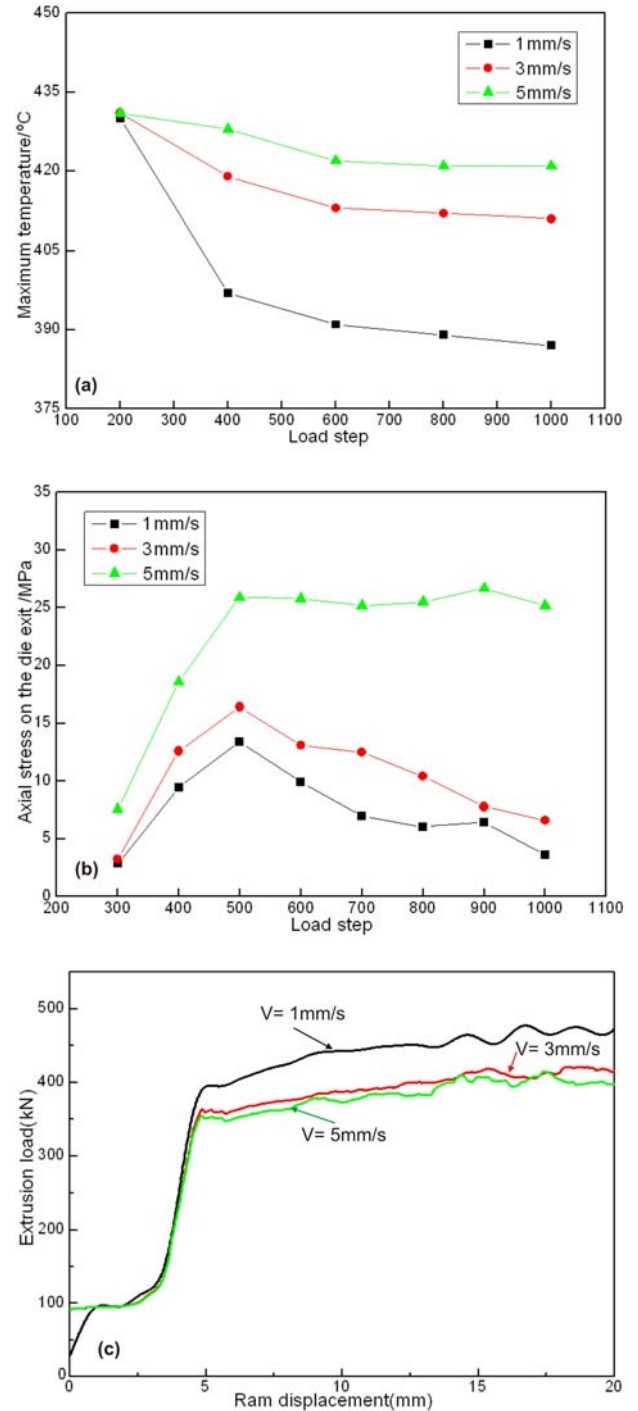
Fig. 3. The extrusion speed's influence on forming process: (a) maximum temperature, (b) additional axial tensile stress, (c) forming load.

value of extrusion load significantly increases, which reaches 15 %.

In order to raise production efficiency, the higher the extrusion speed, the better the production. But an excessive extrusion speed is not only easy to cause temperature rise and additional stress change, which
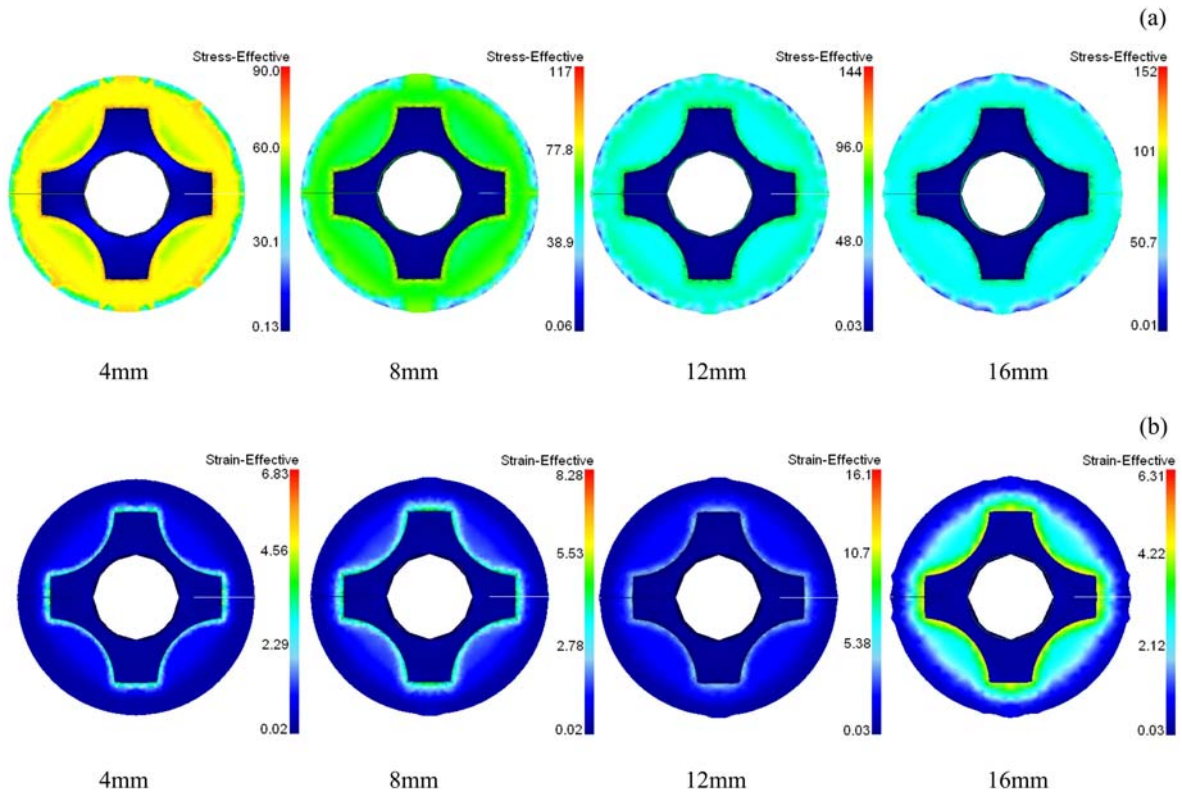
Fig. 4. Distribution of equivalent stress (a) and equivalent strain (b) in the forming process.

definitely affect the mold force condition, thus the increase of extrusion speed can not be unlimited. Considering the interaction of various factors, the extrusion speed 3 mm/s was selected to study the problem.

3.2. Plastic deformation

Figure 4 shows the distribution of the equivalent stress and strain when the ram displacement is 4 mm, 8 mm, 12 mm and 16 mm, respectively.

As is seen in Fig. 4a, the area, which has large equivalent stress in the extrusion process, mainly concentrates in the region which is at the bottom of the mold and the metal has not extruded out yet, the local equivalent stress values increase as the ram displacement increases. We can know from the distribution in Fig. 4b that plastic zone of initial forming only concentrates around the die pocket, and material's plastic deformation did not take place in the other parts. As the ram displacement increases, the plastic zone gradually extends along the radial direction. The degree of plastic deformation in the plastic zone also increases, which can be known from the numerical comparison.

Dead zone is easy to occur at the bottom of the extrusion container due to the characteristics of deformation mode and mold structure. At the same time for the aluminum extrusion, dead zone is easier to be used to improve the product surface quality. There-
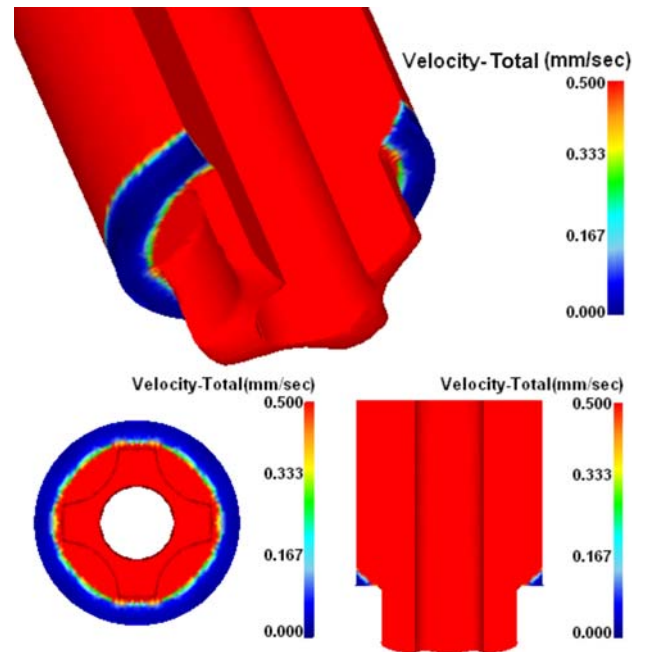

Fig. 5. Distribution of the dead zone.

fore, we need to predict its morphology. What is shown in Fig. 5 is the distribution of the dead zone's morphology with the metal flow speed less than $0.5 \, \text{mm s}^{-1}$.
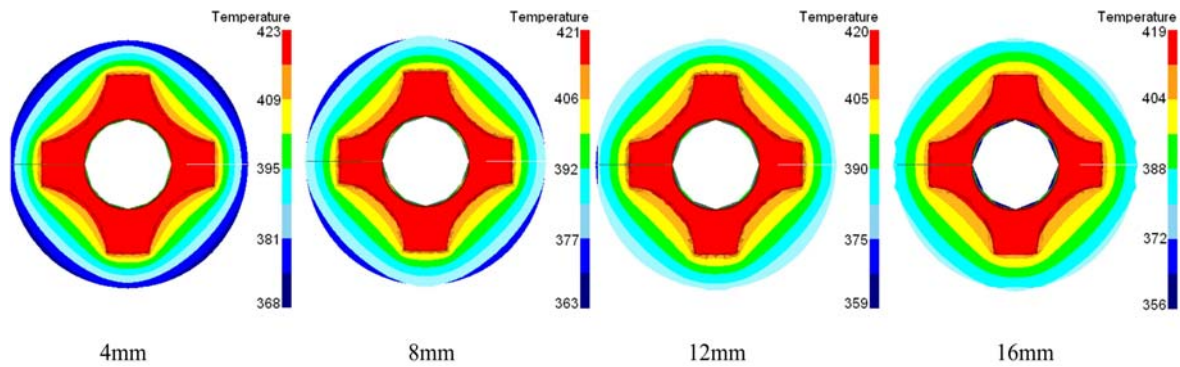
Fig. 6. Contrast of the temperature field's variety at the bottom of the container.

From the distribution of the velocity field in the main section, it can be seen that the dead zone in the extrusion process exists in the corner of the container and distributes like a triangle. The metal in the other regions can be extruded accordingly. It can be seen from the axial side map that the dead zone distributes like a circular ring as a whole at the corner of the container. It is just because of the existence of dead zone that wipes off coarse crystal ring at the outside of workpiece in the extrusion process, which significantly improves the surface quality of extrusion products.

3.3. Temperature distribution

Since extrusion is a complex coupled thermal forming process, the temperature field is always in dynamic change due to the heat transfer and the continuous transformation of thermal power between billet and mold, which affects the product quality significantly. What is shown in Fig. 6 is the contrast of temperature field distribution at the bottom of container in the extrusion process, while the ram displacements are 4 mm, 8 mm, 12 mm and 16 mm, respectively.

From the change of temperature value in the figure we can know that the extruded part in the initial forming process is the high temperature zone, while the corner of the container has the lowest temperature. With the ram displacements increasing, the material deformation would cause the change of temperature increase in each part, the high temperature is still at the extruded region and the peak value of the temperature slightly decreases. However, the minimum temperature increases about 20 ℃ at the corner of the container. It can be seen that the decrease of the temperature gradient value obviously slows from the axis to the around part with the ram displacement increases.

The distribution and change of the isothermal plane with the displacements 15 mm, 30 mm, 45 mm, 60 mm, 75 mm and 100 mm in the extrusion forming process are shown in Fig. 7.

From Fig. 7a it can be seen that the isothermal plane in the container is almost parallel with the axis

except the die pocket high temperature in the initial extrusion. With the extrusion process going on, the temperature in the corresponding parts of container significantly declines, and the distribution's direction would also change. It is shown in Fig. 7b that the isothermal plane shows a trend of gradually increasing along the die pocket, while the temperature of the part near the punch is lower. When the punch continues to go down, a lot of metal is extruded subsequently, and the isothermal plane overall shows a trend of gradually increasing along the die pocket and the value of temperature in the corresponding parts decreases significantly, which is shown in Fig. 7c. As can be seen from Fig. 7d,e,f, the deformation metal in the container in the extrusion process transforms a part of mechanical energy into heat energy. Consequently, the temperature of the blank increases slightly.

4. Conclusions

1. The study of extrusion speed's effect on the forming process suggests that the peak values of the blank temperature all decrease slightly in the range of low-speed extrusion. The decrease of the maximum temperature declines significantly as the extrusion speed increases while the axial additional tensile stress in the die pocket increases accordingly.

2. We can know from the contrast that the plastic zone only concentrates in the region that around the die pocket in the initial forming process and with the ram displacement increasing, the plastic zone extends to the part around along the radial direction. The degree of the deformation also increases later.

3. The high-temperature parts of the mouth are in the die pocket's axis and the value of the temperature decreases gradually with the distance to the axis increasing. However, with the increase of the compression amount, the workpiece temperature decreases and the temperature gradient value slows down obviously.
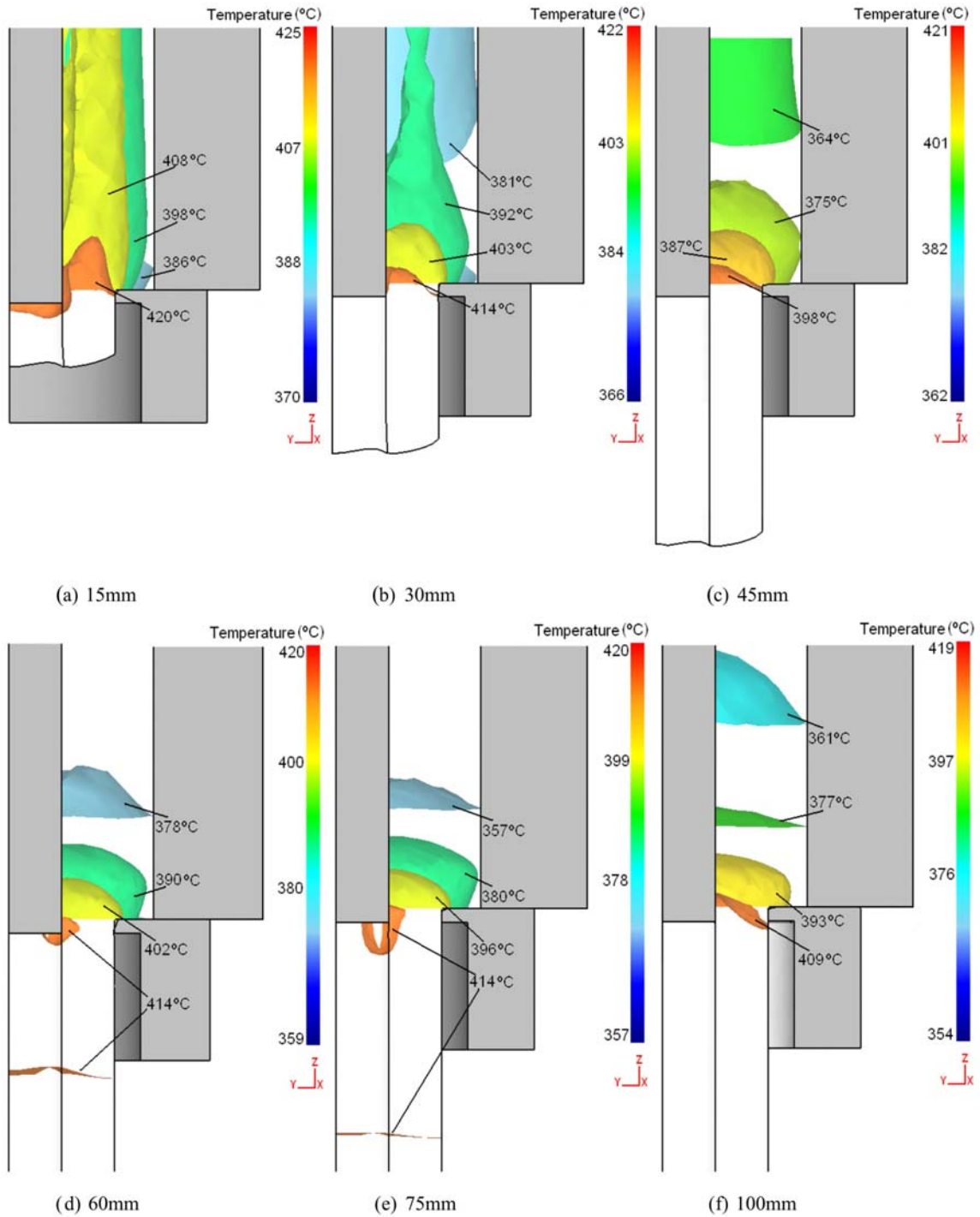
Fig. 7a–f. The distribution of the isothermal plane in the extrusion process.

Acknowledgements

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