Investigation of the Parameters Affecting the Die Failure in High Extrusion Ratio of Aluminium Square Hollow Profile by Using Viscoplastic Finite Element Modelling

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Abstract

The increase of the aluminium profile consumption required the efficient manufacturing process in order to support the aluminium profile product and capacity requirement. The life-time of the extrusion die was one of the important factors that could influence the productivity and quality of the aluminium profiles. This paper was the study of the effect of the extrusion speed on the extrusion load, temperature distributions and the stress concentration in the pothole die. The aluminium square hollow profile size 1.7x1.7 inch with the wall-thickness of 0.7 mm was used in this study. The aluminium initial billet was made of AA6063-T5, which has the diameter of 127 mm and length of 508 mm. This process has the extrusion ratio of about 106, which is considered to be extremely high. Viscoplastic Finite Element Modelling (FEM) was employed to simulate the aluminium hot extrusion process and investigate the results. The simulation results demonstrated that the extrusion load and temperature over the whole extrusion process was not uniform, and the die stress analysis could predict the weak area in the porthole die.

***Keywords**: Aluminium extrusion, Die failure, Finite Element Method*

1 Introduction

Aluminium profile is one of the commercial components used a lot in industries, such as automotive, aircraft and construction industries due to superior corrosion resistance and their lightweight.

The construction industries employed aluminium profile to build and decorate the window flam in the tall building, the transportation industries employed aluminium profiles to build the structure of the aircraft and high speed train to minimize the weight, for example. Due to the particular geometries of the aluminium profiles that have the constant cross-sectional geometries along their length, the extrusion process could be considered as the most suitable process for manufacturing the precise aluminium profiles. Normally, this process can be categorized into two types, forward and backward extrusion [1]. However, the forward extrusion has been employed rather than backward extrusion, because this process is able to extrude the long aluminium profiles. The schematic of the forward aluminium extrusion process can be illustrated in Figure 1.

The principle of aluminium hot extrusion process will be started with the billet preparation, the aluminium rod will be sawed to the suitable length billets, and then both the aluminium billets and extrusion die will be heated up to the temperature of around 470 °C and 440 °C, respectively. The hot extrusion die will be installed on the extrusion machine and the soft aluminium billets will be fed into the container. Thereafter, the ram will move forward to push the soft aluminium billet flow through the extrusion die. Figure 2 illustrated the configuration of the extrusion die, aluminium billet, container and ram in the aluminium extrusion process.

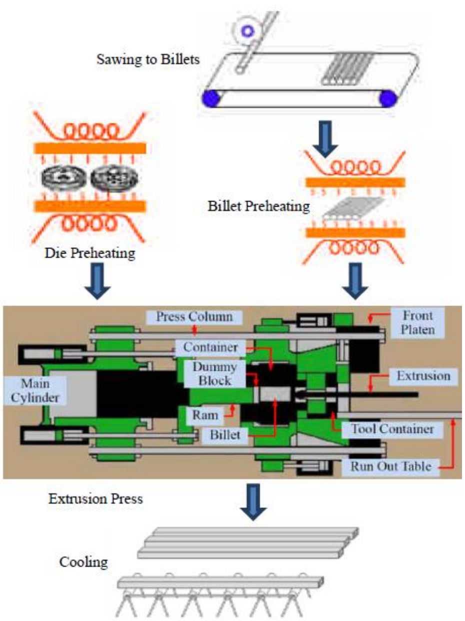

Figure 1: Schematic diagram of aluminium extrusion process [2]

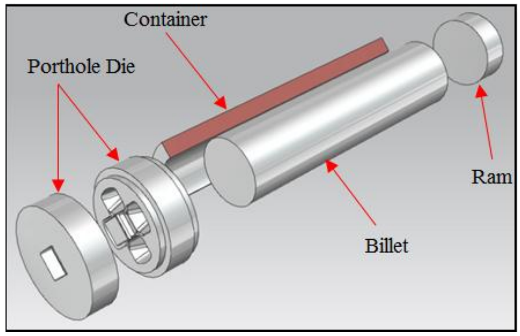

Figure 2: Tools configuration for aluminium extrusion process

Although, the extrusion is the effective process for manufacturing of the desire aluminium profiles, this process is difficult to operate, because the complexity of the cross-sectional geometries of the aluminium profile required by the customers. To manufacture the complex aluminium profile, there are two important factors that the extruders need to be considered, that are the extrusion ratio and the complexity of the cross-sectional geometries. These factors can contribute to the extrusion load, which is the influential factors of the die failure. In the extrusion process, the large extrusion ratio and high complexity profile require high extrusion load.

Therefore, the specific research in this area would be helpful for the aluminium extrusion industries to design a forming die and process to produce the complex aluminium profiles.

2 Literature review

In the recent year, they are many research carrying out to study this extrusion process, these research focused on two main areas; die failure and the applications of FEM for developing the optimum extrusion process.

2.1 *Die failure in aluminium extrusion process*

In the aluminium extrusion process, the die failure can be classified into three modes; a) crack/fracture, b) wear, and c) plastic deformation/deflection [3]. A. F. M. Arif et al. [4] investigated the failure mechanism in the 616 extrusion dies with the 17 different cross-sectional profiles. They revealed that the fatigue facture was the common failure occurring in the extrusion die. Fatigue fracture is normally occurred in the complex geometries in the extrusion die, such as sharp corner, section changes, stamp marks and etc. In addition, the high extrusion ratio and small fillet radii could lead to the fatigue fracture because of the high stress concentration occurring in that area [3]. The initial crack can develop to be the larger size and further become fracture failure. Figure 3 illustrated the crack failure in the porthole die using for extrusion of aluminium hollow profile.

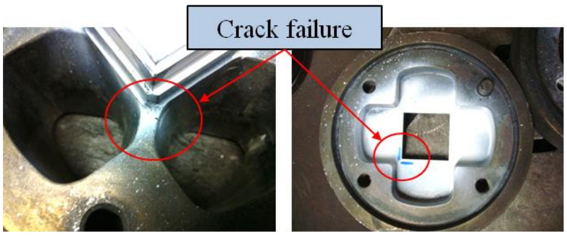

Figure 3: Crack failure in the porthole die [2]

2.2 *Finite Element Method for extrusion process*

Investigation of the interested phenomena in the aluminium hot extrusion process directly is difficult because of the requirement of specific experiment to measure during the extrusion process. Moreover, the experimental testing can be cause of the energy consumption, time and cost. To avoid this problem, FEM would be an alternative tool for investigation the interested phenomena occurring in the aluminium hot extrusion process. The use of FEM for simulation and investigation of the aluminium extrusion process has been studied by many research, such as the analysis of die stress carried out by B. Reggiani et al. [5] and the investigation of elastic deformation (*Die deflection*) of the extrusion die during the process revealed by Jung Min Lee et al. [6]. FEM is not only employed to investigate the die stress, but it is also employed to investigate the temperature distributions during the aluminium hot extrusion process. This method was supported by the research carried out by L.Li et al. [7]. Moreover, the simulation result from FEM can be used to predict the lifetime of the extrusion die, as discussed in S.S Akhtar et al. [8] their team has applied FEM to analyse die stress and estimate the life-time of the extrusion die by considering of fatigue crack. According to the previous study, the FEM is a useful tool for simulation and investigation of the influential factors causing the die failure in the aluminium extrusion process. Therefore, this research would apply FEM to simulate the aluminium hot extrusion process and investigate the results.

3 Simulation models

Simulation of the aluminium hot extrusion process by mean of FEM requires the two important parts, one is geometries of the workpiece and extrusion die, another is the boundary conditions, such as the initial temperature of the billet and die, extrusion speed etc.

3.1 *Geometries model and meshing*

According to the structure of the porthole die using for manufacturing the aluminium square hollow profile, its structure would be considered as the complicated geometries. Therefore, the 3D model of the aluminium billet and porthole die was required to add into the FEM pre-processor. However, simulation with the 3D model requires large computation time because of the large amount of node and mesh contained in the 3D model. To reduce the simulation time, the symmetry plane could be considered. Based on the geometries of the square hollow profile and porthole die, one-eight portions of the whole part could be enough for this simulation. Figure 4 illustrated the symmetry plane and one-eight portions of the 3D geometries required for FEM pre-processor.

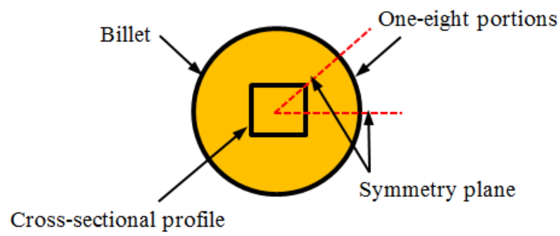

Figure 4: The symmetry plane and one-eight portions of the 3D geometries required for FEM

For this research, Aliminium alloy 6063-T5 was employed to be the billet material, it has the dimension of 127 mm in diameter and 508 mm in length. Porthole die was employed for this process and it consiste of two parts, mandrel and die plate, the porthole die made of the hot-work tool steel AISI H13. The bearing length at the die orifice of about 4 mm (See Figure 2). Thermal properties of the aluminum billet and porthole die were listed in Table 1, The inner diameter of the container was 132 mm, which is bigger than the diameter of aluminum billet 5 mm to provide the small gap for billet inserting.

Table 1: Material properties for work piece and porthole die

Properties	AA6063-T5	AISI H-13
Density (kg/m^3)	2700	7760
Thermal conductivity (W/m-K)	218	28.6
Elastic Modulus (GPa)	70	190

To capture and obtain the accurate simulation results, mesh preparation should be reasonable. For this simulation, the wall-thickness of the aluminium profile was quite thin. Therefore, the absolute mesh was preferred to ensure that the fine mesh is able to flow through the narrow gap at the bearing zone. However, the fine mesh was not necessary in some area. Therefore, the local meshing was employed. With the function of local meshing, the coarse mesh was defined at the circular geometries of the aluminium billet, and the finer mesh was defined at the weld chamber and bearing zone where the material could be severed deformation. The smallest mesh was 0.25 mm located at the bearing zone.

3.2 *Boundary conditions*

Aluminium hot extrusion process has several influential factors that could be related to the quality, productivity and life time of the extrusion die. The extrusion conditions are one of the most important parts that the extruders should consider and control carefully. For this process, the concerned extrusion conditions could be consisted of the extrusion speed, the container temperature and the initial temperature of the aluminium billet and porthole die. These conditions were collected from the real process and added into the FEM pre-processor. In the practice, the extrusion speed could be adjusted by the extruders in order to obtain the qualitative aluminium profile. Therefore, this research would define two different extrusion speeds based on the variable range adjusted by the extruders. However, there are some factors cannot be collected accurately, such as the interface friction factor. The value of this factor could be depended upon the amount and types of lubrication, the surface qualities of the extrusion die, the temperature and the properties of billet material. For this process, the graphite-oil was employed to be the lubrication during the process. Therefore, the suggested shear fiction factor for this simulation would be approximate to 0.2 [9]. The detail of the boundary condition using for this simulation can be seen in Table 2.

Table 2: Boundary condition for simulation

Initial Temperature (ºC)	
Billet	487
Portholes Die	456
Container	420
Ram	315
Interface Friction	
Billet and Porthole die	0.2
Billet and container	0.7
Ram Speed (mm/s)	4.2, 5.2

In this research, DEFORM 3D based on Viscoplastic Finite Element Modelling was selected to simulate and analyze the results. Two simulations were setup according to the two different ram speeds. Then the flow behavior, load and temperature distribution were investigated. One of the simulation result would be taken to investigate the die stress to predict the potential failure area that might be crack and eventually failure.

4 Results and discussions

Die failure in aluminium hot extrusion process can be caused by several influential factors, such as die designs, die material properties, billet material properties, extrusion condition and etc. However, the most common factors that could be the primary cause of die failure would be the extrusion load and temperature. The large extrusion load can increase the stress concentration in the extrusion die, and the increase of temperature can reduce the yield strength of the die material. Therefore, the aim of this simulation is to focus on the flow behavior of material, extrusion load and temperature distribution in the workpiece and extrusion die.

4.1 *Flow behavior and load distribution*

Material flow in aluminum extrusion process is quite important and it can influence to extrusion load. The flow behavior of aluminium during the hot extrusion process is mainly depended upon the structure and geometries of the extrusion die. For this research, the porthole die was used to study and investigate the flow behavior and load distribution. As the simulation results obtained from FEM, The material flow and the extrusion load during the extrusion process of aluminium square hollow profile was not uniform because of the specific die geometries. According to the structure of the porthole die, which consist of two parts, mandrel and die plate, the material flow and the extrusion load could be divided into three phases as illustrated in Figure 5, upsetting, dividing and welding.

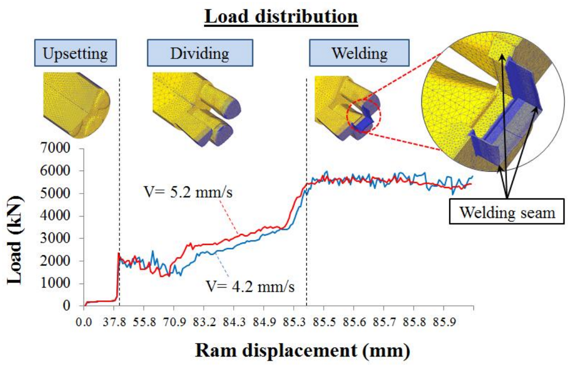

Figure 5: Flow behavior and load distribution in aluminium hot extrusion process

At the beginning of the extrusion process, the diameter of aluminium billet was suddenly increased while the length was reduced, this phenomenon could be the same as the upsetting in the compression test. Then, the soft aluminium would be saparated into four stream corresponding to the amount of the porthole locateed at the mandrel. The extrusion load during the dividing stage was continually increased (See Figure 5). After that, the aluminium stream reached the weld chamber and the welding stage would start. This process cause the increase of the extrusion load and the peak load would be occurred. When the welding process was completed, the alumimiun square hollow profile would leave the die orifice. Due to the shortenning of the aluminium billet in the container over the ram displacement, the contact surface between the billet and container would be reduced. Therefore, the extrusion load after the welding process would continaully dropped as illustrated in Figure 5. Based on this result, it indicated that the extrusion die might be crack while the material weld together because of the occurence of the peak load.

For this research, the extrusion load form both simulation result has a slightly different. During the deviding stage, the extrusion load extrued by the ram speed of 4.2 mm/s was lower than that of the ram speed of 5.2 mm/s. However, the extrusion load after the welding stage was seemed to be the same. These phenomena could be caused by the temperature increasing in case of the faster ram speed, so that the forming load required by the ram speed of 5.2 mm/s could be reduced.

4.2 *Temperature distributions*

At the beginning of aluminium hot extrusion process, the aluminum billet was preheated up to the suitable temperature. Therefore, the initial temperature distribution in the whole aluminium billet would be uniformed. However, the temperature distribution during the extrusion process could be varied due to energy loss occurring from the plastic deformation of material, the interface heat transfer between the workpiece and the extrusion die, and the temperature drop due to environment. For this research, the simulation results showed that the temperature distribution of the aluminum billet was not uniform. Figure 6 illustrated the maximum temperature occurring in the workpiece. The maximum temperature would occur at the weld seam plane where the material welds to form the square hollow profile. As a result, the extrusion speed is not significant influencing to the temperature distribution as showed in the slight difference of the maximum temperature (See Figure 6 a and b). This result indicated that the maximum temperature of the porthole die could be occurred at the leg tip of the mandrel corresponding to the maximum temperature of the workpiece.

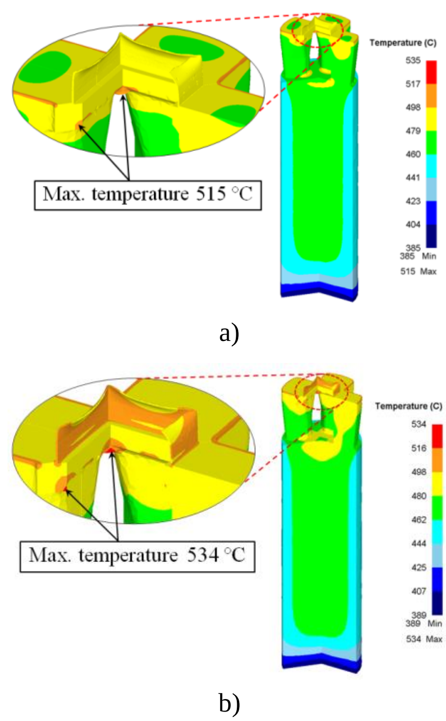

Figure 6: Temperature distribution in the workpiece during the aluminium hot extrusion process, a) ram speed 4.2 mm/s and b) ream speed 5.2 mm/s

Although the temperature at the weld seam plane was increased, the simulation results also revealed that the temperature of the aluminium billet could be dropped especially at the back-end of the billet, this result could be cause by the temperature loss due to the colder ram. However, this phenomenon would not affect the process, because the extruders will give the safety stroke approximately 30 mm at the back-end of the aluminium billet to avoid the temperature drop at the back of the billet. Figure 7 illustrated the maximum and minimum temperature distribution in the whole billet.

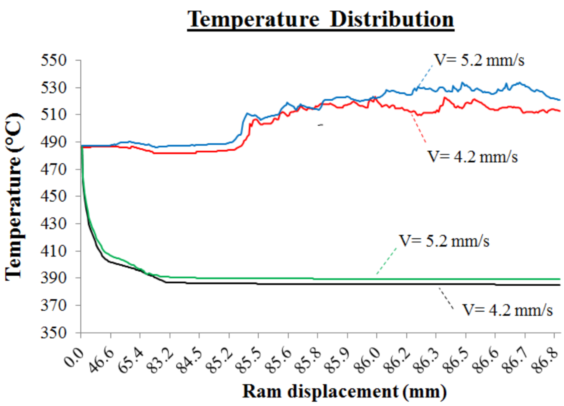

Figure 7: Temperature distribution at the several ram displacement

4.3 *Die stress analysis*

Based on the simulation results that the maximum extrusion load occurred by the extrusion speed of 4.2 mm/s, this simulation result was taken to analyze the die stress. The aim of die stress analysis is to investigate the stress concentration in the porthole die and predict the weak area that is more likely to be failure. To analyze the die stress, the peak reaction force was interpolated from the workpiece, the mandrel and die plate was fixed as the same in the real process. The result of die stress was illustrated in Figure 8. The die stress analysis showed clearly that the critical part of the porthole die located at the die leg by the maximum tensile stress of 1710 MPa. This part could be a potential failure by crack, which is coherence to the die failure found in the real die (See Figure 3). For the die plate, the maximum tensile stress occurred at the corner closed to the bearing of the die plate.

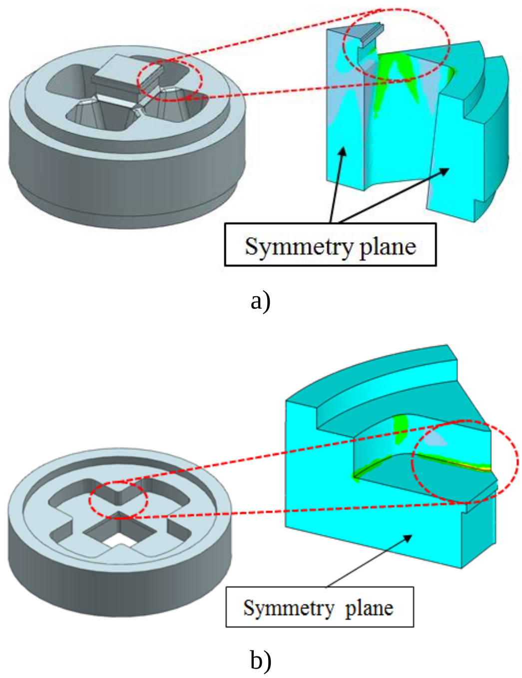

Figure 8: The weak part of the porthole die, a) mandrel and b) die plate

According to the geometries of the porthole die that there is the mandrel to create the square hollow of the aluminum profile, this part would connect to the bearing and it could provide the death metal zone while material flow through the bearing. Figure 9 showed the flow stream of material and death metal zone at the mandrel. Therefore, the stress concentration at the undercut of the mandrel was investigated. Figure 10 and 11 illustrated the tracking point for die stress investigation and the stress distribution at the death metal zone.

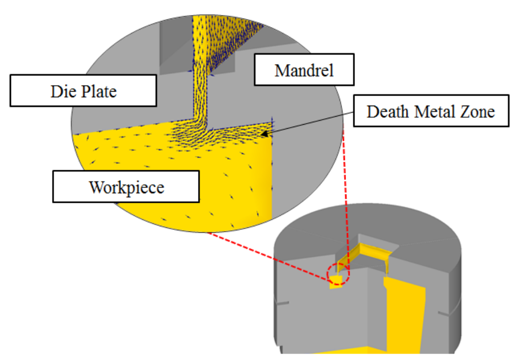

Figure 9: Flow stream of material and death metal zone at the mandrel [2]

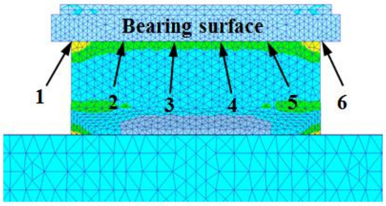

Figure 10: Illustrated the tracking point for investigation of die stress at the death metal zone

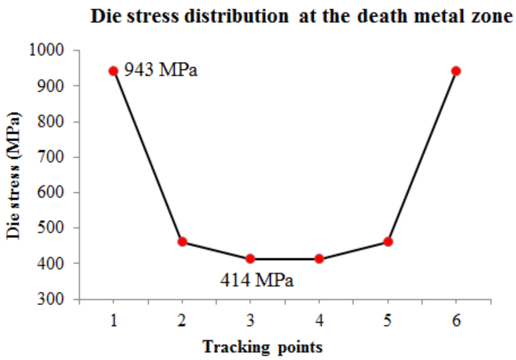

Figure 11: Die stress distribution across the death metal zone

The result demonstrated that the stress distribution across the death metal zone was not uniform. The maximum stress occurred at the sharp corner of the bearing with the stress of 943 MPa. This result indicated that the sharp corner of the mandrel bearing is more likely to be failure by the fracture, and this result is coherence to the failure mechanism in the extrusion die studied by A.F.M. Arif et al. [4].

5 Conclusions

According to the simulation results predicting the failure area, the aluminium extrusion process could be simulated by means of FEM. The interested phenomena, such as flow behaviour, extrusion load, temperature distribution and die stress could be revealed and analysed. Based on the simulation results, the extrusion load and the temperature were not uniform. These results indicated that the fatigue can be generated due to the cyclic load and temperature. Therefore, the aluminium extruders and die designers should concern the number of extrusion cycles that the porthole die can undergo. Moreover, the die stress occurred in the porthole die should be minimized by the optimization of the extrusion conditions and die geometries.

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