

3D Numerical Simulation to Investigate the Influential Factors Causing Die Failure in Hot Aluminum Extrusion of Square Hollow Profile

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Abstract -- Nowadays the aluminum alloys have been used worldwide in different industries, such as the building industry, automotive industry and aerospace industry. The demand of different cross-sectional aluminum profiles is still continuously increased to support the growth of different industrial sections. To produce these aluminum profiles, the design of the forming die plays a significant role to improve the part accuracy and production capability. Currently, there are many companies tried to improve performance of process and extend the die life by conducting different sets of experiments. This method is time-consuming and so costly. Finite Element Modeling (FEM) just recently is used to design the product of the part. However, there are a few studies on the process parameters affected the die life. Therefore, this project focuses on the effect of the factors that could be caused of shorten die life, such as flow behavior, extrusion load, flow velocity, and temperature distribution. FEM was employed to simulate and investigate the effect of those factors on die stress. DEFORM 3D was used to simulate this hot extrusion process of aluminum square hollow profile size 1.7x1.7 inch. The simulation result of die stress was predictable and coherent with failure in real die that used to produce aluminum profile. Furthermore, this result was able to indicate, where is the weakest areas, which should be modified or adjusted die geometry to reduce die stress and improve die life.

Keywords -- Aluminum hot extrusion process, die life improvement, die stress analysis, FEM, hollow profile, numerical simulation, porthole die

I. INTRODUCTION

Hot extrusion process has been used to produce aluminum profiles for many years. This process is a continuous process. As a result, the production rate is very high by comparing to other processes. Therefore, the hot extrusion process is considered to be the most appropriate processes for a mass production. The products produced by this hot extrusion processes have been used in many industrial sectors, for example construction industry, automotive industry and aerospace industry. There are many types of the cross sectional profiles obtained from this process. Therefore the tolerance and precision including die and forming process

condition are quite important and directly influenced to the quality of desired profile geometry. To obtain and achieve in term of quality and productivity, the manufacturers should optimize and control those factors carefully. The typical hot aluminum extrusion process can be explained in Fig 1. The process begins with billet preparation. The billet and die were heated to achieve the required temperature of 487 °C and 456 °C, respectively. Later, the heated die would be installed on the extrusion machine while the billet was loaded into the container. When this process was completed, the hydraulic cylinder pushes the ram forward to compress the hot billet flowing through the die and form to the desired cross sectional profile. During this stage, all of the conditions need to be precisely controlled to ensure the qualities of products, otherwise some defects can be occurred, such as poor quality of surface and weld-seamless in case of hollow profile. Furthermore, the die failure can be occurred if process conditions are not suitable.

In aluminum hot extrusion process, the forming die plays an important role on this process to obtain the precise aluminum profile. Most of aluminum profile manufacturers want to improve the performance of extrusion process and expect to achieve on the good qualities of aluminum profile in order to meet customer requirements with the possibly minimum production cost. However, in reality they cannot completely be succeeded with their expectation, because some problems are occurred commonly. Tool and die failure too soon is one of the concerned issues in aluminum hot extrusion process, such as crack-based fracture, wear and plastic deformation/deflection [1,2].

For the porthole die, these kinds of failure always occurred at the same position. For example, the wear always occurs at the bearing surface, and the fracture always occurs at the sharp corner of the mandrel. Fig. 2 illustrated some types of the crack occurring at (a) base of mandrel and (b) the corner of the pressure die. This failure is caused by the exceeding die material fractural strength especially at the weld chamber and fatigue effect.

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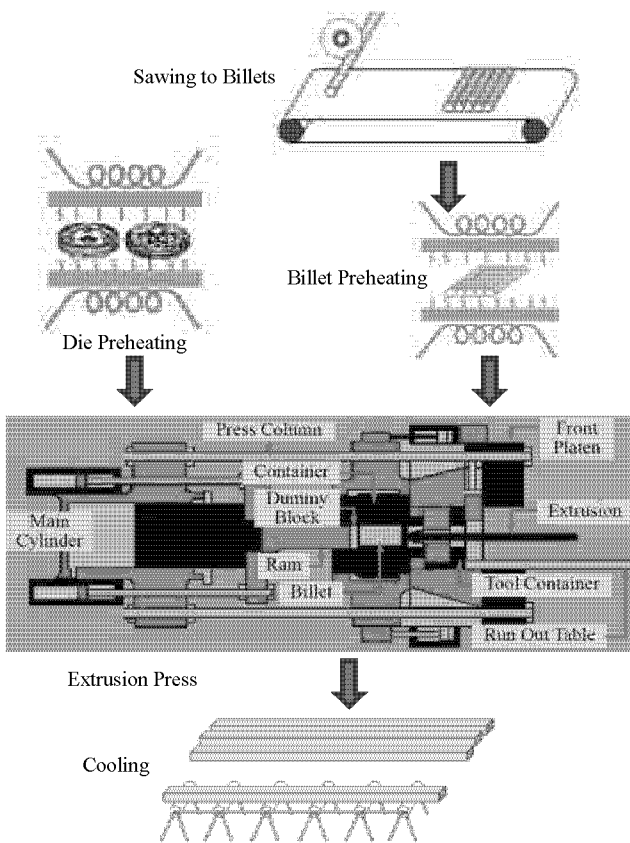


Fig. 1 Schematic diagram of hot aluminum extrusion process

Die failure can be directly related to the qualities of extruded profile. For example, the poor surface qualities of aluminum profile will be appeared when the wear is occurred.

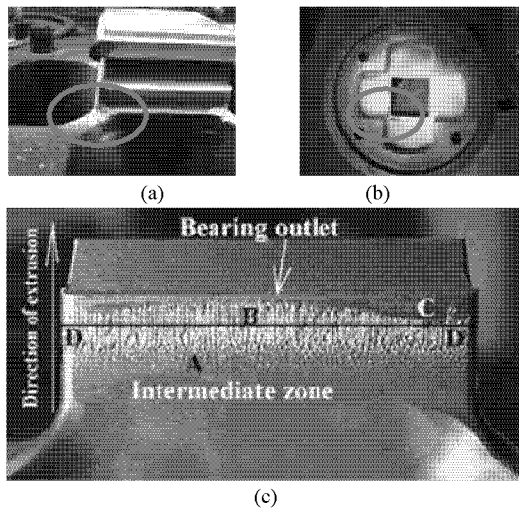


Fig 2. Example of die failure in porthole die, (a) and (b) Crack failure, (c) wear failure, [1]

In aluminum hot extrusion process, there are many influential factors that lead to the occurrence of die failure, such as the geometries of porthole die, extrusion conditions, billet geometries and the precision of extruded machine. These

factors are caused of the variation of extrusion loads, temperature distributions and velocity, which are the main causes of the die failure.

These factors are concerned by the aluminum profile extruders for many years. Based on these factors, adjusting of the extrusion process conditions is one of the alternatives that the extruders have been preferred in practise, such as ram speed and billet preheat temperature, because adjusting by this way is easier when the porthole die is under the extrusion process. However, the extruder should understand the effect of each condition. Otherwise, the die failure will be occurred sooner than expected.

Currently, there are many research being studied the effect of extrusion conditions and propose the way that could reduce die failure. The results from the previous research revealed that the extrusion load and temperature during the aluminum hot extrusion process is non-steady. The temperature of porthole die was increased continuously over the whole process, especially in the first few shots because the initial temperature of billet is higher than that of the porthole die [3]. Furthermore, the extrusion speed related to the temperature variations [4] and extrusion load, such as the workpiece temperature would be increased when the extrusion speed increases, and the forming load is also increased [5]. Although the extrusion speed is constant, the temperature distributions in the one cycle process are not stable. As a result, the temperature of workpiece increases continuously until the end of the process[6]. These results had proposed by some researcher by using finite element modeling. This method became useful alternative ways for the predicting the effect of extrusion conditions and optimizing the suitable geometries of the porthole die [7].

Based on these results that have been proposed by the previous research, the extrusion speed or ram speed had significantly influence to the temperature and extrusion load which is the main cause of die failure. Therefore, the objective of this paper is to investigate the effect of ram speed and then analyze die stress to find the forming die could be failed.

II. SIMULATION MODELS

In aluminum hot extrusion process, there are many conditions that must be controlled, such as the initial temperature of billet, die temperature, ram speed and billet dimension. These conditions were directly related to the qualities of aluminum profile and also influence the die life. In order to simulate and obtain the result correctly, each condition were collected directly from the experiments which have been used to extrude a square hollow profile. For this research, the billet material was AA6063, with the dimension of 127 mm in diameter and 508 mm in length. Porthole die was used as a tool for manufacturing aluminum square hollow profile size 1.7x1.7 mm, and wall thickness was 0.7 mm, the bearing length was 4 mm. Real porthole dies that have been used to produce this product was illustrated in Fig. 2 a,b, the dies were made of AISI H13. Thermal properties of billet and porthole die were list in Table I, The inner diameter of container was 132 mm, which is bigger than the diameter of billet 5 mm to provide the small gap for billet inserting.



TABLE I
MATERIAL PROPERTIES FOR WORK PIECE AND PORTHOLE DIE

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

Before starting the simulation, there are many necessary conditions that have to be collected, such as the initial temperature of the billet and porthole die, container, and ram speed. To obtain the accurate results, these conditions have been collected from the real extrusion process, and to investigate the influence of extrusion speed 2 mm/s in ram speed was defined to compare the result later. These data can be seen in Table II.

TABLE II
BOUNDARY CONDITION FOR SIMULATION

Initial Temperature (°C)	
Billet	487
Portholes Die	456
Container	315
Ram	315
Interface Friction	
Billet and Porthole die	0.3
Billet and container	0.7
Ram Speed (mm/s)	5.8, 2

In this research, DEFORM 3D was selected. To reduce the computational time, the one-eighthth portion of workpiece and porthole die was used, and then the boundary conditions was defined and entered into the preprocessor of FEM. After the simulation was completed, load distributions were analyzed to find in which stroke the simulation provides the maximum load, and the die stress analysis would be simulated at the maximum load in order to investigate which part of porthole would have the maximum stress which exceeds the fracture die strength.

III. RESULTS AND DISCUSSIONS

In order to investigate what can be causes of die failure, the specific results were defined and considered. First of all, the load distribution and flow behavior at several strokes have been observed as the specific result. Then, the temperature distribution was investigated and die stress analysis was simulated to find what part of porthole die can be the weakest area.

A. Load Distribution

Due to the structures and geometries of the porthole die are quite different from that of the flat die, the flow behavior of material in porthole die was also definitely different. Flow behavior in porthole die can be classified into three stages; upsetting, dividing and welding stage. Fig. 3 illustrated the flow behavior of aluminum stream at several stages. During upsetting stage, the diameter of a billet started to increase

while the length was reduced similar to the upsetting process. Then, the aluminum billet was separated into four streams in order to fulfill the space in the weld chamber of porthole die.

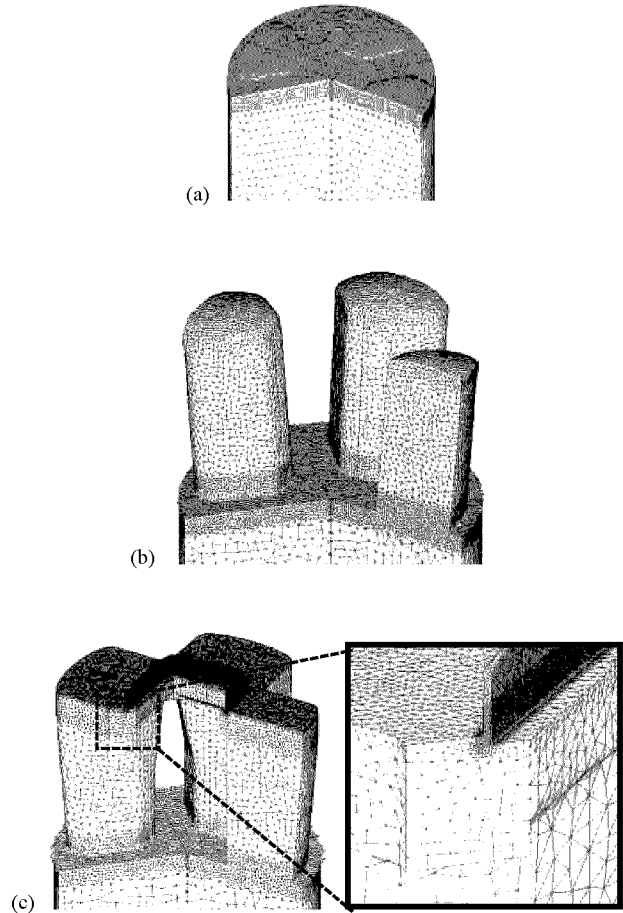


Fig. 3 Flow behavior on different stage, a) Upsetting stage, b) dividing stage, c) welding stage and weld seam plane

Based on the difference of flow behavior in each stage, the extrusion load would not be constant including the stable condition. Fig. 4 illustrated the distribution of extrusion load with respect to the ram displacement, and this graph shows the comparison of load with different ram speeds (2mm/s and 5.8 mm/s). This results revealed that the extrusion load is significantly increased at the beginning of process as the upsetting load. Then, it would drop a little bit and seem to be constant in the dividing stage. Since the material reached the weld chamber at the ram traveling around 76 mm, the extrusion load started to increase again in order to weld and form the cross-sectional profile. Finally, the square hollow profile was flowed out through the bearing of porthole die (see Fig 3).



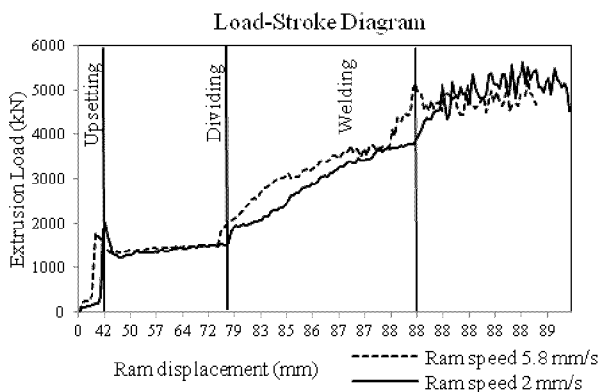
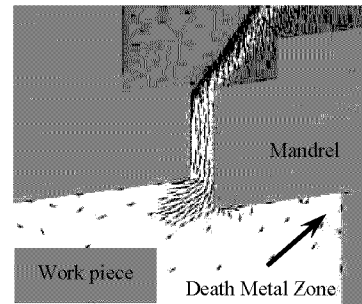
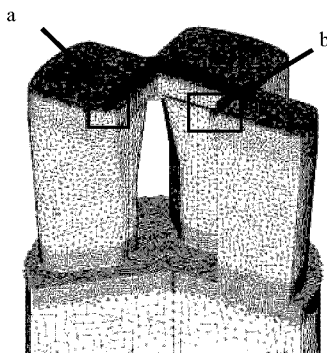


Fig. 4 Comparison of extrusion load

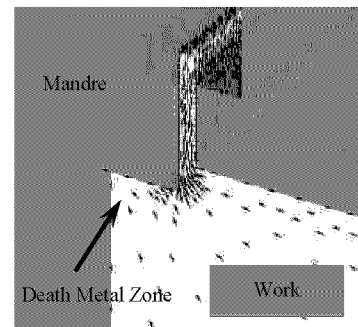
B. Flow Behavior and Exited Velocity

Wear is one of the failure modes in porthole die, which have been seen commonly at the bearing surface, especially in the hot extrusion process. In addition, flow behavior associated with exited velocity might be the causes of this problem, such as imbalance exited velocity and flow stream of material in the weld chamber.

Therefore, the flow behaviors of material in porthole die have been observed in FEM simulation. Fig. 5 illustrated materials flowed over the bearing surface, and also revealed the direction of flow stream and death metal zone, which could be the causes of wear and fracture at the mandrel. In this result, the sectional plane along the weld seam and weld chamber were demonstrated in Fig. 5 a,b, respectively. The velocity vectors illustrates the flow stream direction of the material that there was some amount of material flow into the death metal zone, furthermore there is some amount of material pointed on the mandrel surface as represented by blue arrow in Fig. 5 a,b. This situation provided the possibility of failure at the sharp corner of mandrel if the porthole die has been undergone the cyclic loading during the process. By considering the flow direction of material, the wear failure is could be occurred at the mandrel surface rather than bearing surface.



(a)



(b)

Fig. 5 Flow stream. (a) Flow stream at the weld seam section, (b) Flow stream at the weld chamber section.

Beside the flow behavior, the exited velocity on the cross-sectional profile (see Fig. 6) is another factor that needs to be considered because too fast or imbalance exited velocity could lead to exponentially increase the wear rate at the specific location, especially at the bearing surface. Fig. 6 illustrates the measurement location of exited velocity around the cross-sectional profile, and Fig. 7 illustrates the exited velocity at different locations along the workpiece cross-section (See Fig.6 for the location) of different ram speeds. The results showed that the ram speed relates to the exited velocity. The higher the ram speeds (5.8 mm/s) the faster the exited velocities, and the fastest exited velocity occurred at the location number 2 and 4 (24.1mm/s) while the lowest velocity occurred at the location number 1 and 5 (23mm/s). These results indicated that the possible location of wear would be located at the location number 2 and 4 rather than any other locations. For the condition of lower ram speed (2 mm/s), the result indicated in the opposite way that the maximum velocity occurred at the corner of the cross-sectional (21.9 mm/s). Although the lower ram speed gave the lower exited velocity, if considering this result in term of practical process, the ram speed of 2 mm/s is unable to use because the imbalance exited velocity which can effect to tolerance of cross-sectional profile flow.

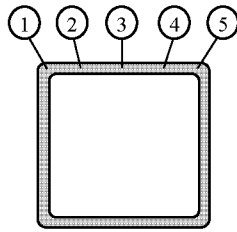


Fig. 6 Cross-sectional profile and measurement location of the exited velocity

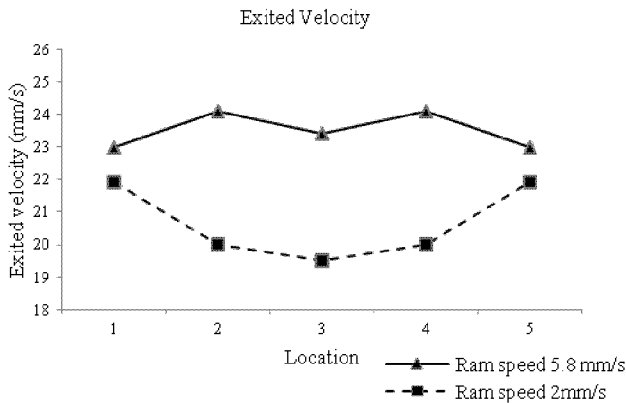


Fig. 7 Exited velocity around cross-sectional profile.

C. Flow Behavior and Temperature Distributions

There were many influential factors that can be caused of die failure in porthole die. Temperature distribution was another important factor that should be concerned in term of extrusion load and wear. According to the results from the previous researchers, the extrusion load reduces when the temperature in the whole workpiece increase. In practise, the temperature of the workpiece during hot extrusion process is not constant, and the temperature distribution during the material flow through porthole die is not uniform. Therefore, the temperature distribution of workpiece should be analyzed, especially at the bearing surface. Fig. 8 a,b illustrate the temperature distributions of the whole billet at the ram speed of 5.8 and 2 mm/s, respectively. The maximum temperature occurred at the bearing area, and the higher ram speed provided the higher temperature (501°C) which located at the corner of cross-section as shown in Fig. 9. The temperature distribution at the all-over the cross-section of hollow profile was not uniform, and higher variation of temperature at the bearing will occur if the ram speed increases, this result might cause by the deformation of material and shorter contact time between billet and container. Fig. 10 illustrate the temperature range of the workpeice at the beginning of process. The results demonstrate that the temperature of workpiece was reduced continuously, especially at the interface of the container and the billet because the initial temperature of container and porthole die is lower than that of the billet, thus the heat should transfer to the container and porthole die through their contact interface, and if comparing with the temperature range along the ram displacement, lower ram speed will give the lower temperature range because the maximum temperature was drop rapidly due to longer contacting time, that would lower the upper temperature down.

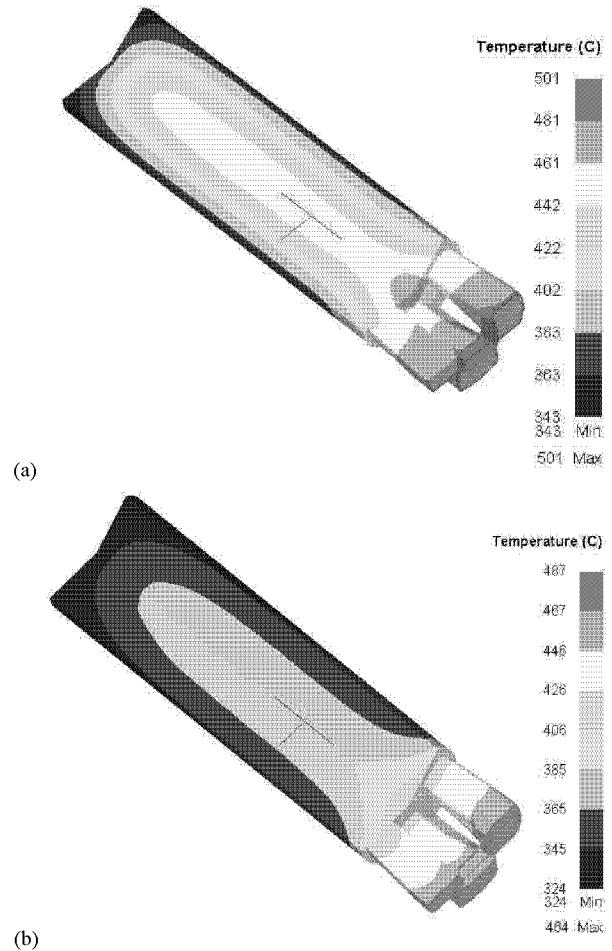


Fig. 8 Temperature distribution for the whole part, a) Ram speed 5.8 mm/s, b) Ram speed 2 mm/s

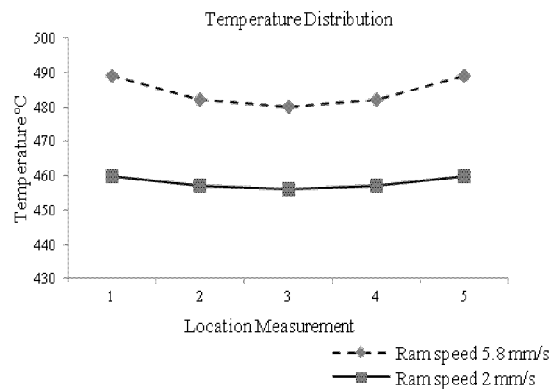


Fig. 9 Temperature distribution at the bearing



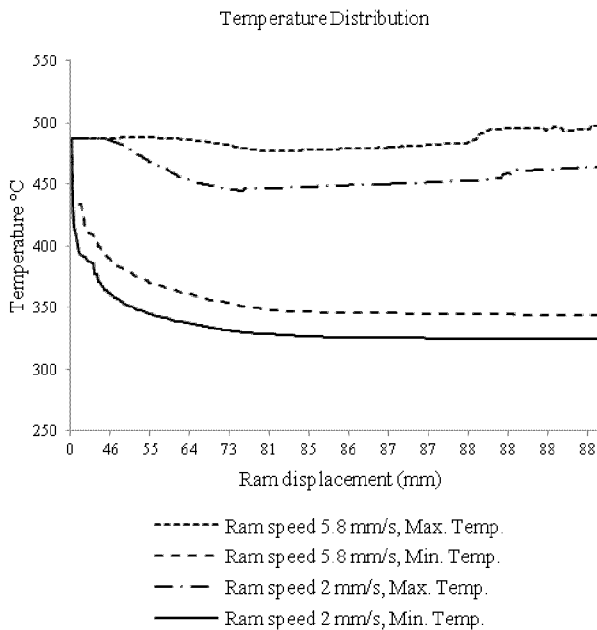


Fig.10 Temperature distribution in the whole part

In aluminum hot extrusion process, the isothermal and the lowest extrusion load should be expected to improve die life. However, it is impossible to control and fix the precise temperature in the practical process. Fig. 11 represented the combination of temperature range and extrusion load in the aluminum hot extrusion process. According to the results that, the variation of ram speeds provided the different extrusion load and temperature distribution. Ram speed of 5.8 mm/s gave the temperature in the range between 343.6-497.9°C and the maximum load was 5,737 kN. Ram speed of 2 mm/s gave the temperature in the range of 324.5-487.1°C and the maximum load was 5,617 kN. Then these data were plotted and calculated at the different areas as demonstrated in Fig. 10. The results indicated that obtained from ram speed of 5.8 mm/s was smaller than 3.2% when comparing with that of the ram speed of 2 mm/s. Therefore, with these results, the ram speed of 5.8 mm/s should be recommended to reduce die failure.

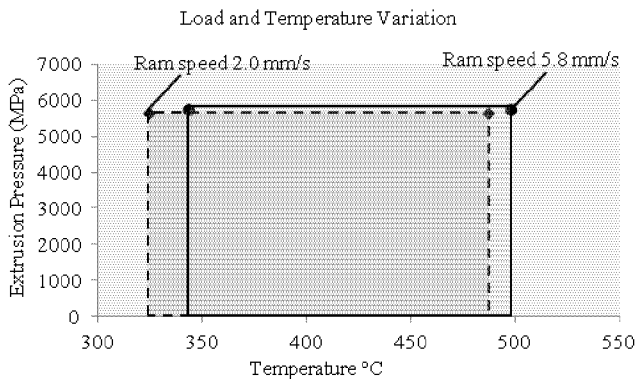


Fig. 11 Extrusion load and temperature variation in aluminum hot extrusion process

D. Die Stress Analysis

In order to investigate the maximum die stress and weak area of the porthole die that might be cause of die failure, the result of FEM with ram speed 5.8 mm/s was analyzed. The objective of die stress analysis is to locate the weakest areas of the porthole die, and compare the result of die failure with the real porthole die that have been used in the practical process. In the real porthole die, there were two failure areas that have been seen commonly, it was crack at the die leg and corner of bearing in pressure die due to tensile stress as indicated with the circle on Fig. 12. The result of die stress analysis was illustrated in Fig. 12, 13.

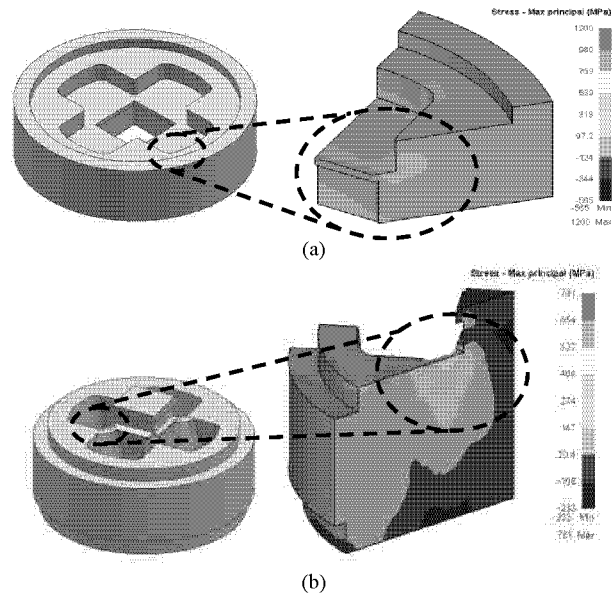


Fig. 12 (a) Die stress analysis of pressure die, (b) the weakest area of pressure die

The result of die stress analysis represented clearly where the weakest area of porthole is, the weakest point of the pressure die was at the welded chamber area, with the maximum stress of 1,200 MPa, while the weakest areas of the mandrel occur at the die leg with the maximum stress of 781 MPa. With this result, the weakest areas were coincided with the same location at the real porthole die during the experiment.

Another issue of the die stress analysis was the die elastic deflection. To achieve in term of precision or dimension of extrudate, manufacturer should concern about the die deformation or distortion during hot extrusion process, because it can lead to the dimensional error and fatigue.

The maximum die displacement of mandrel was 0.152 mm along z axis, this number occurred at the contact surface between billet and die during the beginning stage. It was undergone by compressing the load that supply billet and ram. However, this part of porthole die is not significantly impacted by precision of extrudate. The important part of porthole die that can be a problem of extrudate precision is at the bearing area, and the die displacement at this area was 0.0749 mm which came up at the corner of mandrel. For pressure die, the



maximum displacement was 0.0595 mm, and it occurred at the bearing area, especially at the center of bearing surface.

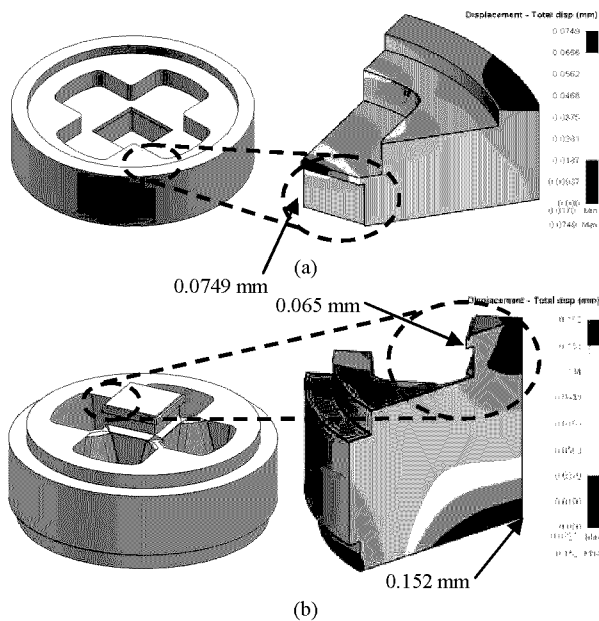


Fig. 13 Die displacement analysis, (a) pressure die, (b) mandrel

V. CONCLUSIONS

Based on the result from FEM, the influential factors that can be caused of die failure in porthole die were investigated, such as flow behavior, extrusion load, exited velocity and temperature distribution. Without FEM these factors were difficult to be determined. For this paper, the flow behavior during aluminum hot extrusion process provide the unstable extrusion load, the highest extrusion load occurred during the welding stage, during this stage can be caused of the crack failure at the die leg. Flow velocity and flow stream reveal the death metal zone at the mandrel that can be caused of the fracture failure at the sharp corner of the mandrel. For temperature distributions, the highest temperatures generated at the bearing zone that can be caused of increasing wear rate at the bearing surface, and also occurred at the weld seam. Die stress and die deformation during hot extrusion process revealed that the result was coherent with failure mechanism in the real porthole die. According to these results, FEM was quite useful for the die designers to optimize die geometries and process condition to enhance the die life and achieve a better product quality of the aluminum hot extrusion process.

IV. ACKNOWLEDGMENT

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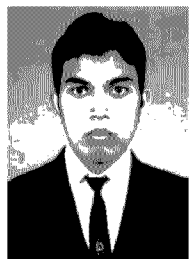
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VI. BIOGRAPHIES



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