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Numerical simulation of aluminum extrusion using coated die

Tushar Bakhtiani, Hazim El-Mounayri, Jing Zhang *

Department of Mechanical Engineering, Indiana University-Purdue University Indianapolis, Indianapolis, IN 46202, USA

Abstract

In aluminium extrusion, the life of the die tooling components is mainly limited by wear and fatigue. Therefore reliable predictions of the amount of wear and its distribution in dies are important factors for the die design. In this study the stress location and wear depth of the tooling components were calculated using finite element models incorporating the Archards wear model. A comparative study was conducted on an extrusion die without coating and with a bilayer (TiCN + Al_2O_3) chemical vapor deposition (CVD) coating. Stress distribution and the amount of wear were calculated. The results generated from the simulation would help predict the service life of the components through optimizing coating thickness.

Selection and Peer-review under responsibility of the Chairs of The 1st International Joint Mini-Symposium on Advanced Coatings between Indiana University-Purdue University Indianapolis and Changwon National University, Indianapolis.

Keywords: Wear; aluminum; extrusion; coating, modeling, Archards model, finite element

* Tel.: +1-317-278-7186; fax: +1-317-274-9744.
E-mail address: jz29@iupui.edu

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1. Introduction

Aluminum Extrusion is a metal forming process used for mass production of aluminum products with constant cross section profiles such as rods, tubes, beams, wires, multi-porting tubes etc. The most commonly and widely practiced type of extrusion in the industry today is the direct extrusion process, also known as the billet on billet extrusion. In the direct extrusion process the hot aluminum billet is pushed through the profile opening of a die by the ram in a hydraulic press with a force typically in the range of 1000-3500 ton (See Fig 1).

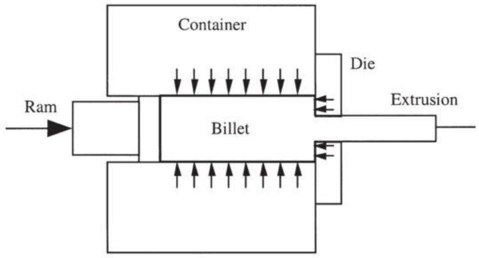


Fig. 1. Aluminium extrusion (reproduced from [1])

To ease the deformation process and to minimize the occurrence of work hardening; dies are pre-heated to 850-950 ˚F which prevents the aluminum from sticking in the profile opening, while the billets are pre-heated to 900˚F before it enters the press causing it to enter a plastic state while maintaining its solid shape. The container is also heated to 750-800 ˚F to prevent the billet from cooling down. As the aluminum is extruded, the temperature of the final extrudate might span between 1000-1150 ˚F due to friction and internal deformation occurring at the bearing land [2]. In order to maintain a straight product and to avoid folding due to high temperatures of the final extrudate, a tensioner is required to maintain a slight plastic stretch of the final profile until it cools down to a solid state.

The process is semi-continuous. One billet is extruded within a couple of minutes after which the extrusion is paused to introduce a new billet hence known as the billet on billet extrusion. Before the new billet is introduced into the container the outer skin of the billet accumulates in the back of the billet due to high friction between the container and billet. This is known as the back end defect, and is sheared off because the outer layer contains coarse iron-rich intermetallic and Mg_2Si precipitations that are not suitable for extrusion[2]. The aluminium from the new billet welds on to the material left in the die at the next press stroke, causing a continuous product to exit the die. The region where the new billet welds onto the old billet is known as transverse weld; which is clearly visible on the extruded product. The transverse weld is typically scrapped due to its reduced mechanical properties and surface finish.

During extrusion, high values of compressive forces are developed by the reaction of the billet with the container and die components thus causing a demand on the tooling material of an extrusion die to have high levels of hardness, yield strength and toughness at elevated temperatures along with good resistance to wear and corrosion. Also, it should be suitable for surface treatment or surface coating. Those demands are best fitted by hot work steels, materials commonly used in extrusion dies. As a result of high stresses that occur during extrusion, the die tooling components fail due to fatigue and wear, more specifically due to excessive wear of the bearing surface which causes a change in the cross section of the extrudate as well as resulting in poor quality of surface finishing of the product. A common practice in the industry is to nitride the tooling components to improve its wear resistance thus increasing tool life. Another common practice which is new to the extrusion industry to improve tool life is using surface treatments of a combination of different chemical or physical vapor deposition (CVD and PVD) coatings[3].

According to an investigation carried out by Stahlbergh and Hallstorm [4] more than 70% of die replacements are due to wear during extrusion , thus it is important to understand the effects of coating on die components as they help prolong the die life during extrusion[4]. Zhang has investigated die wear behavior during aluminum alloy 7075 tube extrusion. In his investigation based on modified Archards wear model numerical results were generated using Deform-3D that show process variables having multiple effects on die wear behavior[5]. Bjork has investigated the effects of wear on surface treated dies for aluminium extrusion through surface-coating by physical vapor deposition

(PVD). In his study of understanding the life limiting mechanism of gas nitirted tools and duplex coated tools, Bjork estimated that the duplex coating prolongs the tool life at least five times as compared to conventional nitriding. This is due to the superficial PVD layer shows a combination of high resistance to mechanical wear and resistance to corrosive attack by hot aluminium[6].

Experimental tests of extrusion dies are time consuming, expensive and difficult to control. There is a need for a simplified evaluation method to evaluate the amount of wear that a tooling component experiences during the extrusion process. Since the computing technology has vastly advanced in the past decade, the main purpose of this study is to develop a finite element analysis model that can handle large scale plastic deformation to conduct a comparative study on the modular die design mandrel and die plate made out of powder metal (PM) tool steel without coating and with a bilayer chemical vapour deposition (CVD) coating of (TiCN + Al_2O_3) to locate to maximum stress locations and to calculate the amount of wear that occurs during hot aluminium extrusion. The insight gained from this study will be utilized to improve the die design of the tooling components in order to improve die life and will also be implemented to evaluate further design models.

2. Die model

Figure 2 shows the cross-section shape and dimensions of the aluminum profile to be extruded in the present study. The extruded profile is commonly known as a micro-multi-void tube, the width of the profile is 0.6383 inch, the height of the profile is .07 inch, the thickness of the top and bottom wall is approximately 0.01462 inch and the thickness of the wall between each void is 0.0103 inch

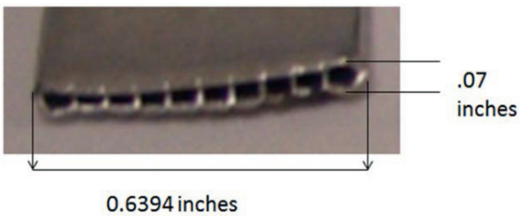


Fig. 2. Extruded profile

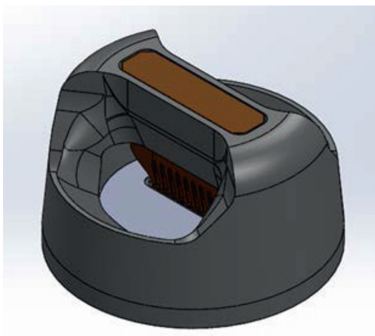


Fig. 3. Modular die

The profile shown in figure 2 is achieved through a porthole die design that consists of a die plate and mandrel (see Fig 3). This allows the extrusion of hollow profiles having multiple voids.

The modular die (porthole die) is assembled into a die tooling assembly which consists of a die ring, holder die cartridge, mandrel, die plate, spacer and backer. All these components are assembled together to provide the structural strength needed for the tooling to withstand the high compressive forces of the extrusion process (see Fig 4a and b).

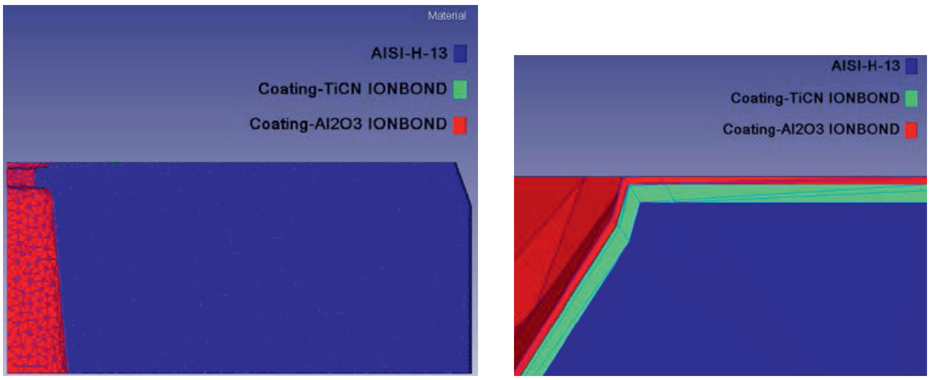
(a) (b)

Fig. 4. (a) Assembly exploded view; (b) modular die tool stack

All the components shown in figure 4a are assembled together to form the modular die tool stack which consists of 8 ports (8 strands of the profile can be extruded at once). The outer diameter of the entire tool stack is 11.81 inch and the total height of the tool stack is 5 inch. The die components are press fitted and assembled careful to avoid movement of the components during the extrusion process.

3. Simulation setup

The finite element package, Deform-3D was used to numerically model the extrusion process. The simulation system is designed to analyse the three-dimensional (3D) flow of complex metal forming processes. The choice of finite element software to use was dictated by multiple factors: needs to handle large scale plastic deformation associated with extrusion, allows to generate a bilayer surface mesh for coating (shown in Fig 5), predicts the amount of tool wear that occurs on a component during extrusion, predicts loads over the entire range of extrusion process (i.e. upsetting of the billet until steady state extrusion) and most importantly predicts stresses the components undergo during the extrusion process for optimization of die design.



(a) (b)

Fig. 5. (a) Bilayer coating surface mesh; (b) magnified view.

The modular tool stack comprises of 8 cavities which would take a lot of time to simulate and generate results. Thus, in order to save computation cost and time the modular die tool stack was reduced to one sixteenth of its original geometry due to symmetry. The simulation model also consists of a ram, container and billet to mimic the actual hydraulic press used for extrusion (see Fig 6).

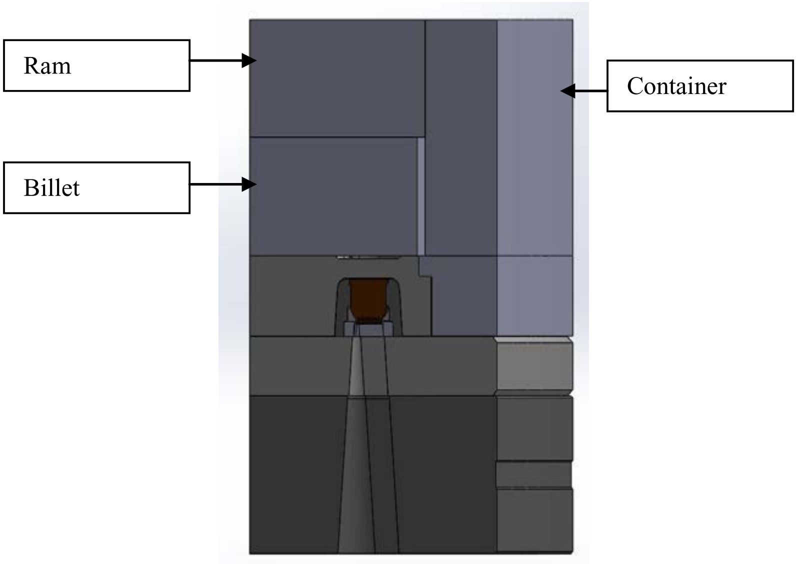


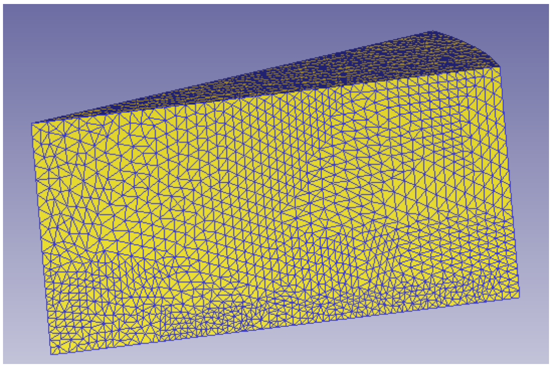
Fig. 6. Simulation model

Aluminum alloy 3003 series and H13 tool steel were chosen as the billet and tool materials, respectively. To analyze metal flow, temperature, wear and deformation behavior during the extrusion process, the billet was modeled as a plastic material whereas; the other tooling components were defined as rigid objects during deformation. To control the element number and ensure calculation accuracy; especially in the concerned areas (i.e., mandrel and die plate) several local mesh windows with a higher element density and finer elements were applied (Figure 7).

Table 1 provides data for the coating mesh applied on the mandrel and die plate. In the simulation, these components were defined as rigid objects in order to calculate the tool wear based on the Archards wear model. H-13 tool steel is the base material of the components on which the bilayer CVD coating is applied (see fig 5).

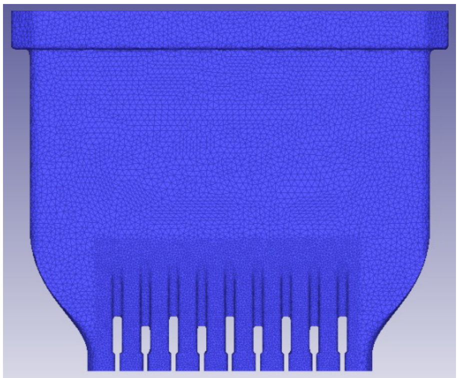
Table 1: Material data used in the model

Mechanical/Thermal Property	Unit	TiCN Coating	Al2O3 Coating	H-13 Tool Steel
Young's Modulus	Ksi	3907.75	60190.7	30500
Poisson's Ratio		0.23	0.22	0.3
Thermal Expansion	1/F	4.444e-06	4.25e-06	6.5e-06
Thermal conductivity	Btu/sec/in/F	0.0003356	0.0003607	0.0003264
Density	Klb/in^3	1.83346e-04	1.43245e-04	7.28773e-07



(a)

(b)



(c)

Fig. 7. (a) Billet mesh; (b) die plate mesh; (c) mandrel mesh

Due to high temperatures and pressures of the extrusion process, it is difficult to obtain experimental data for the friction among the container, die and billet. Friction is one of the most important process parameters that influence the extrusion load, extrusion temperature and flow of aluminium at the die bearing land. It also has a major effect on the amount of wear that occurs on a tooling component which is a concept that the die manufacturers are trying to understand better to reduce service life of their dies that fail due to wear either by optimizing die design or material used for the die components. At present, friction mechanism during aluminium extrusion has not been thoroughly understood and mathematically expressed, therefore it has been acknowledged as the most uncertain parameter in the finite element simulation for aluminium extrusion[7]. In the present study, a coulomb friction model was utilized to represent the friction among the billet and tooling components. A coulomb friction coefficient of 0.4 was assumed at the billet and tooling component interface to represent the sliding contact, while a coulomb friction coefficient of 0.9 was assumed at the billet container interface for being highly sticky since no lubrication applied among the billet and container. The friction coefficients were provided by a local extrusion company based on empirical knowledge of the extrusion process.

The Archard's wear model Eqn. (1) was implemented to calculate the wear depth as the aluminium is extruded through the modular die components; which is widely used to analyse wear behaviour of dies. In this model, the wear depth is proportional to the wear coefficient (K), interface pressure (P), and relatively sliding velocity (V), while it is inversely proportional to the die hardness (H):

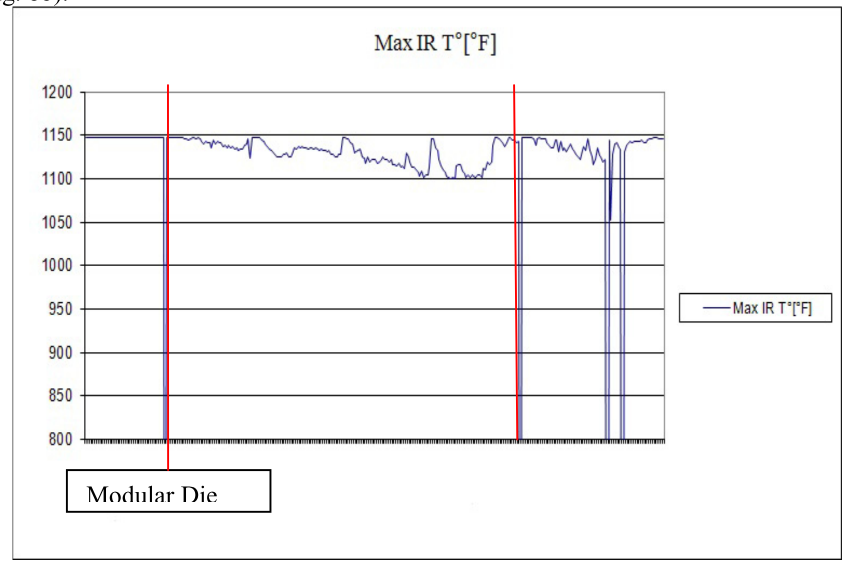
$$W = \int \frac{p^a v^b}{H^c} \qquad (1)$$

The exponents, *a*, *b*, and *c*, for interface pressure, sliding velocity and hardness are experimentally calibrated however they are considered 1 for a, b and c is considered 2 for common tool steels. Hardness for H-13 tool steel was set at 50RC and for bilayer coated components hardness was set at 54 RC. The hardness information was provided by the materials local vendor. The wear coefficient is generally calculated through experimentation of the material, however, in this study no such data was available for the CVD (TiCN + Al_2O_3) bilayer coating (Figure 5), hence the wear coefficient (k = 2.426e-5) was calculated from the modified Archard's wear model present in [5], in which die wear behaviour during aluminium extrusion was validated through the number of billets ran through the modular die through previous data presented by the extruder [5].

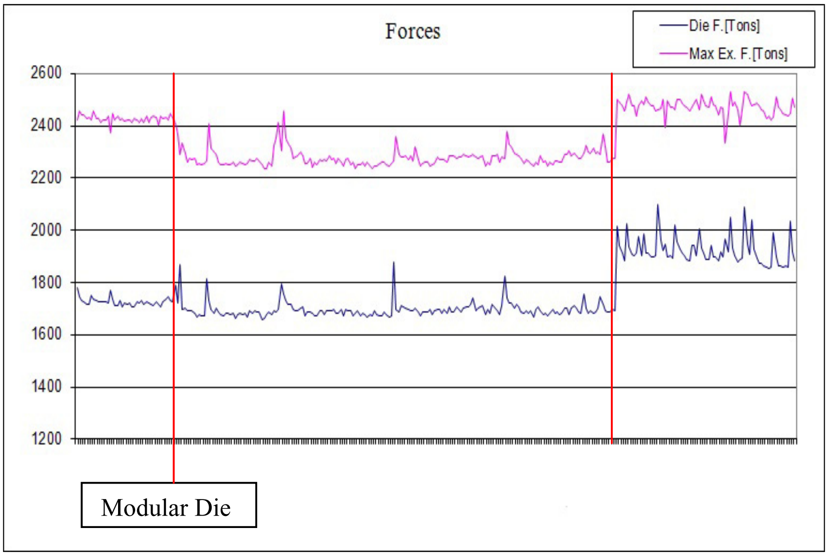
According to the process parameters provided by a local extrusion company, the initial temperatures of the billet is defined at 900 ^{o}F with an 80 degree taper and the initial tooling temperature is defined at 850 ^{o}F, respectively. The heat transfer coefficient between billet and die is set for 0.002 Btu/sec/in^2/F and the heat transfer coefficient between tooling and die is set at 0.003 Btu/sec/in^2/F. In addition, symmetric planes were assumed to be fixed with no material moving across due to the use of one-sixteenth of the model. The extrusion ram speed was defined at 6mm/s (provided by a local extruder who has previously used the modular die design). The simulation was setup to stop after the ram has been pushed down 0.45 inch, and the simulation information was setup to save every 10 steps. The length of the simulation step was defined in terms of ram displacement, and each step is defined as a constant value of 0.01 in/step.

4. Model validation

To validate the simulation model results obtained were compared to the measured data provided by a local extrusion company that has previously extruded aluminium through the modular die design. The criterions for validation of the simulation model consisted of the exit temperature of the profile (1150 ^{o}F – 1100 ^{o}F) (Fig. 8a), maximum load (2300 ton – 2450 ton) peak at the break through phase into steady state extrusion and dead metal zone formation (Fig. 8b).



(a)



(b)

Fig. 8. (a) Experimentally measured profile exit temperature; (b) experimentally measured force on ram and die in continuous extrusion

In Fig 9 it can be seen that the model is able to capture both the breakthrough and steady state extrusion phase. In the A stage, the extrusion ram begins to contact the billet and then forces the aluminum to fill the gap between the billet and the container. The extrusion process in this stage is known as upsetting of the billet with the container, where the metal flows in the axial direction. In the B stage, material is continously forced to flow along the radial direction and to fill out the gap, so the required extrusion load rises rapidly until stage C. At the starting point of stage C the billet is now completely in contact with the cylinder and the forces rise rapidly to fill the smaller cross section of the porthole die until its peak value is reached after which it begins a steady state extrusion.

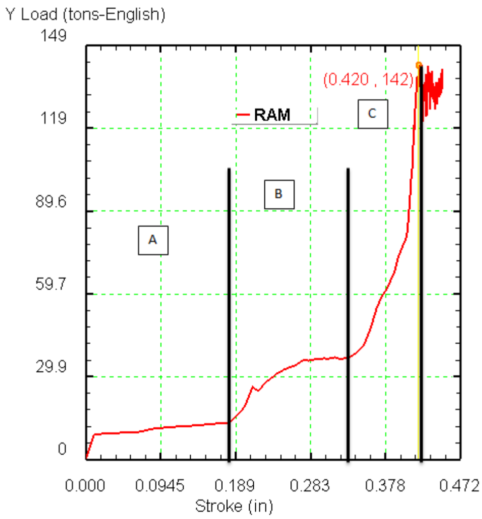


Fig. 9. Simulated load-stroke curve

Figure 10 shows the exit temperature of the profile to be around 1070 ˚F. There is a 6.9% difference in the simulated exit temperature as compared to the measured exit temperature (Fig 8a).

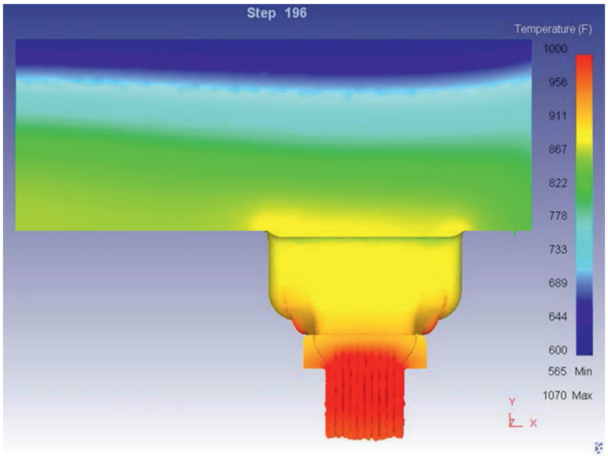
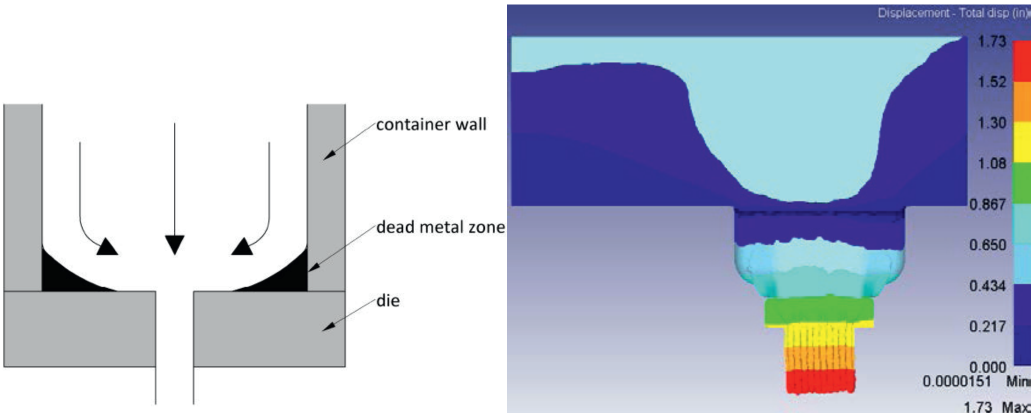


Fig. 10. Temperature Distribution in extruded billet

Dead metal zone formation was also validated using deform simulation. Based on the previous study on material flow during extrusion [2], it has been observed that metal at the billet and container interface move slower than the material at the center of the porthole as shown in Fig 11.



(a) (b)

Fig. 11. (a) Dead metal zone reproduced from [2]; (b) simulated dead metal zones formation

5. Results and discussion

The temperature distribution of the billet during extrusion states that the maximum temperature is at the bearing region. It is also observed that the highest temperature on the mandrel and die plate exist in the bearing location as well. Since the final shape of the extruded profile is formed in this region and it is the smallest cross section, maximum plastic deformation occurs in this region thus causing high temperatures [8].

As the simulation results shown in Fig 12, it is observed that the coated mandrel and die plate have a higher temperature gradient as compared to the non-coated components. The maximum temperature of the non-coated die plate and mandrel is 890˚F and 911˚F, whereas the maximum temperature of the coated die plate and mandrel is 897˚F and 922˚F. This is directly related to the thermal conductivity of the coating which is higher compared to the non-coated parts. From Fig 12, we can see that the areas with high temperature concentration are also the area where maximum tool wear occurs. However, temperature is not a function of wear in Archard's model that is used to calculate the tool wear therefore temperature cannot be directly related to tool wear. Also, it is beneficial to have higher temperatures in the tooling during extrusion as it allows for the aluminum to flow better giving the final profile a better finishing surface.

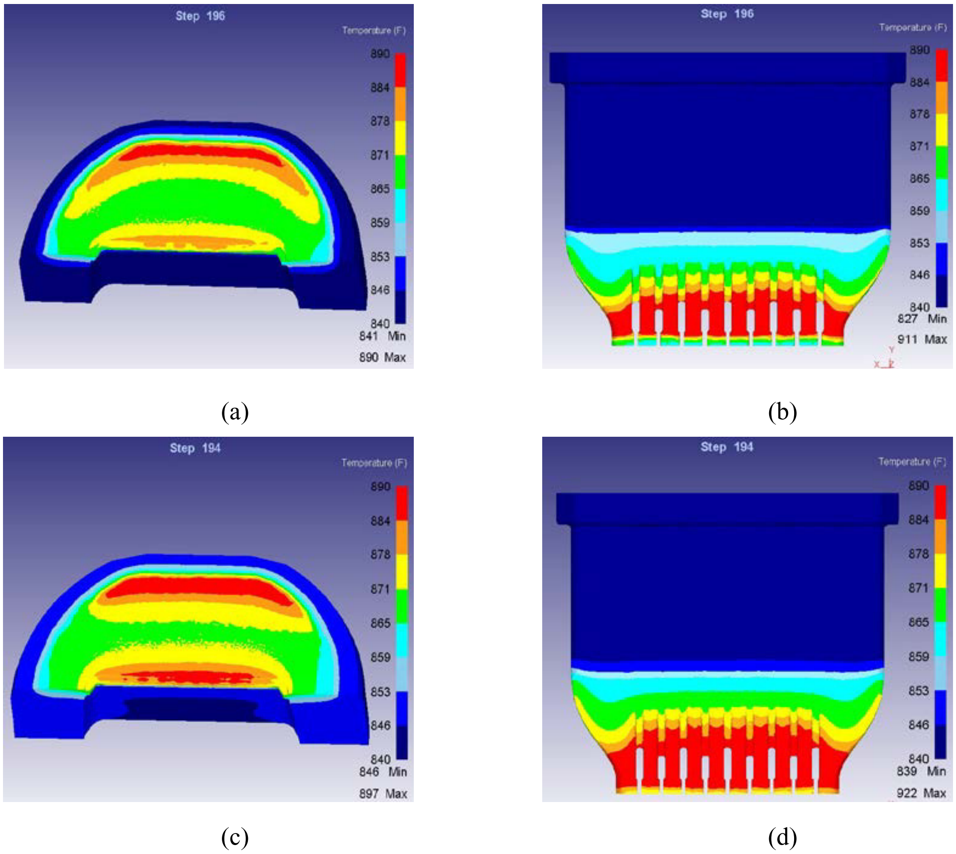


Fig. 12. (a) Non-coated die plate temperature distribution; (b) Non-coated mandrel temperature distribution; (c) coated die plate temperature distribution; (d) Coated Mandrel temperature distribution

The maximum temperature fields in both cases can be seen towards the outer end of the die plate and bearing region. When we look at the flow of the aluminum in this region it is observed that as the aluminum flows vertically down towards the die plate, it is then split into two flow fields one towards the bearing and the other towards the end of the die plate (Fig 13) to fill the void. This flow of the billet towards the back end of the die plate causes the high temperature distributions seen in Figures 12 (a) &(c) as well as causes tool wear occurring on the die plate shown in Figure 14.

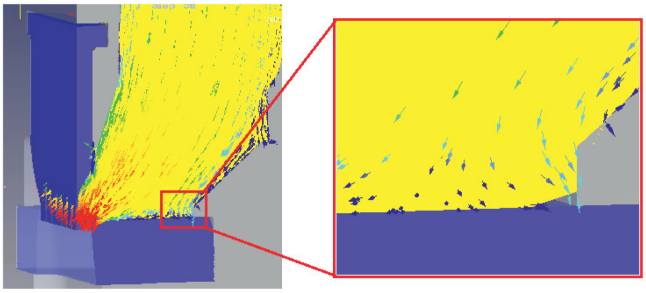


Fig. 13. Simulated velocity vector plot of aluminium flow

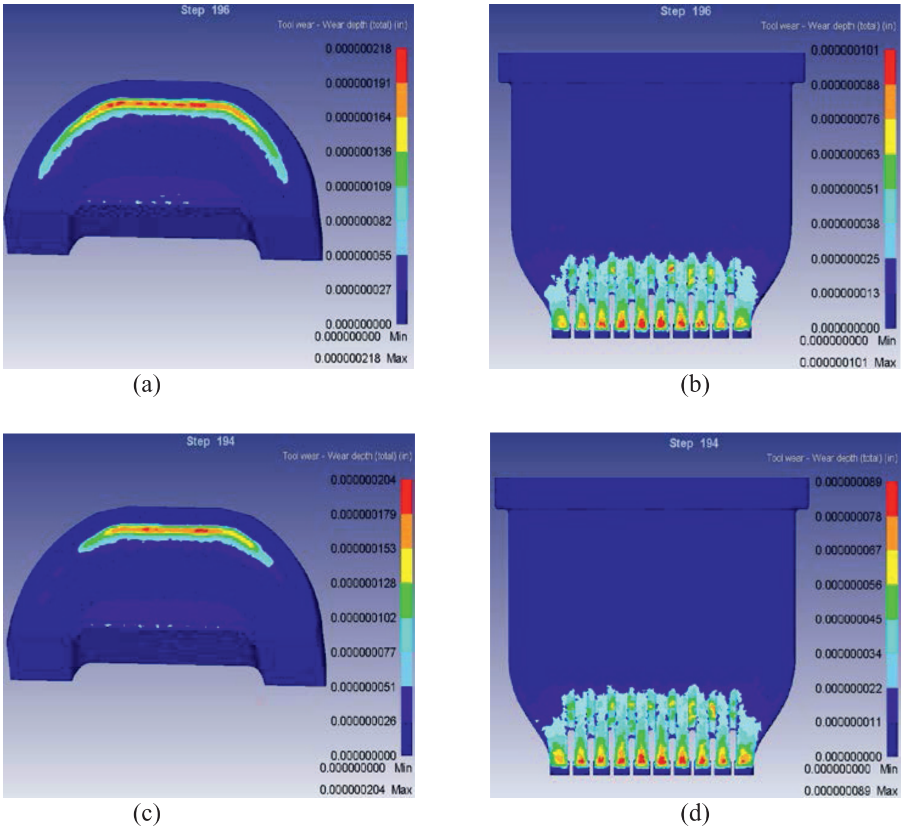


Fig. 14. (a) Non-coated die plate wear depth; (b) non-coated mandrel wear depth (c) coated die plate wear depth; (d) coated mandrel wear depth

Figure 14 compares the wear distribution in the mandrel and die plate. According to the Archards wear model, the wear coefficient (k), sliding velocity (V) and interface pressure (P) is directly related to wear while the hardness is indirectly related to wear. To understand the simulated results, it is assumed that the sliding velocity and interface pressure is constant at each step, the wear coefficient is a constant value set forth by the user based on the literature review conducted, and the hardness of the coated and non-coated components have been measured at 54 RC and 50

RC. From the simulation results, it is observed that the coated mandrel has a wear depth of 8.95e-08 inch, the coated die plate has a total wear depth of 2.04e-07 inch; whereas, the non-coated mandrel has a total wear depth of 1.01e-07 inch and the non-coated die plate has a total wear depth of 2.18e07 inch. In both of the tooling components it is observed that the non-coated parts have a higher tool wear than the coated parts.

Figure 15 helps in validating the tool wear observed in the simulation on the modular die design after it ran 60 billets, the simulation results show the localized areas of maximum wear occurring in the similar regions as shown in Fig 15, thus validating that having a bilayer coating on the mandrel and die plate prolongs the die life.

Fig. 15. Image of modular die showing the wear pattern

From figure 15 it can be observed that the aluminium flows in two directions just like the aluminium flow seen in Figure 13. The split flow of aluminium causes wear of the coated parts thus reducing die life. It is also observed that the wear region on one side of the die is more than the other thus it can be deduced that aluminium flows faster on one side of the die than the other. Another assumption made for the deform simulation is that the coating layer is free from cracks and burs. When the mandrel and die plate are coated the surface generally has small cracks or burs that during aluminium extrusion increase the wear rate due to abrasive and adhesion wear. The results generated from the simulation provide a benchmark for the extruder to test the optimized die design and compare it with the results generated for the coating simulation thus giving the die manufacturer a rough estimate of the service life of the die.

6. Conclusion

A finite element model incorporating Archards wear model was successfully develop to simulate aluminum die extrusion process. Stress distribution and the amount of wear were calculated. The exit temperature, maximum load on ram during breakthrough stage, and dead metal zones were simulated. The results are in good agreement with experimental data. Wear simulations showed that the coated tooling had a higher resistance to temperature and wear than uncoated one. The results generated from the simulation would help predict the service life of the components, and can be used to optimize the right amount of thickness needed for the coating to improve die life.

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