Investigation of forming speed and friction on drawability of Al 5182-O using a servo press with CNC cushion

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Abstract

Forming speed and lubrication affect parts quality and productivity in automotive industry. Servo presses, increasingly used in the automotive stampings, have the capability to provide variable ram motions for various stamping operations. In the present study, deep drawing tests were conducted in a servo press to investigate the effects of forming speed on the drawability for Al alloy (5182-O) sheets at room temperature. Two lubricants, dry film lubricant and commercial mineral oil lubricant, were evaluated under different ram motions, respectively. A non-isothermal finite element (FE) model was used to design and analyze the deep drawing tests under various forming speeds. Experimental results showed that deeper draw depths could be achieved when applying higher forming speeds. The dry film lubricant was found to provide extremely low friction coefficient, compared with the oil-based lubricant. However, the dry film lubricant showed more sensitivity to the changes of forming speed. The punch load was shown to decrease with increasing forming speed in the tests. The temperature increase, induced by plastic deformation and friction work, was also estimated by using the thermal-mechanical FE model at each drawing speed. The results and discussions give insights into the effects of forming speed on deep drawing process of aluminum alloys at room temperature.

Keywords:

Forming speed; Drawability; Al alloy; Non-isothermal FE model

1 INTRODUCTION

Aluminum alloys are playing a significant role in automotive manufacturing, due to their high strength and light weight. However, forming of aluminum alloys presents new challenges because of aluminum's low formability. Deep drawing is the most common process used in sheet metal forming. Considering the drawability and quality, drawing of Al parts could be affected by several factors, such as material properties, tool geometry, interface conditions and process parameters [1]. Among various proven results, forming speed was found to have particular effects on deep drawability of Al alloys. In a recent study, it was found that not only a higher forming speed could help enhance the draw depth of an experimental aluminum alloy door panel, but also the increase in the forming rate affects drawability [2]. Several reasons were suggested to explain the effects of forming speed on the drawability of aluminum alloys at room temperature, such as stain-rate and temperature dependent material properties, heat generation at critical locations and friction force varying with sliding speed [1, 3-5]. Especially, the relationship between the coefficient of friction and the sliding speed was investigated by using strip drawing tests. Results demonstrated that the punch speed has a significant effect on drawing force [5]. To reduce development time and cost, finite element method (FEM) offers special advantages in sheet metal forming analysis. With the FE-based inverse analysis, a reliable and practical methodology was developed to evaluate the performance of different lubricants using deep drawing test. The performance of some tested lubricants was found to change with contact pressure and ram speed [6]. By using FE models, the optimal ram speed could be estimated which is beneficial to prevent failures [7]. Additional studies have focused on the effects of deformation and friction induced heat on the formability of advanced high strength steels (AHSS). Maximum temperatures 86 ºC in the deformed cup (DP590) and 46 ºC in the die corner were predicted by using non-isothermal FE simulations [8]. In drawing aluminum alloys, the small temperature rise (32 ºC) in the die corner was predicted by an analytical model in strip drawing. Adhesive wear, as a result of local peak stresses, was found in the same location [9].

Considering the practical aspects of forming, the application of servo drive presses continues to increase in blanking, deep drawing and warm forming of light weight alloys [10]. The most impressive advantage of servo press is the free slide motion control, such as reverse motion, variable-speed and acceleration/deceleration functions [11]. For deep drawn parts such as door panels and fenders, it is verified that the draw depth and productivity have been improved by using a servo press line [12]. The special slide motions, such as pulsating and stepwise drawing motions, controlled by hydraulic press or mechanical servo press, were successfully applied in drawing operations to prevent wrinkles and cracks [11, 13].

The main objective of the present study is to investigate the effects of forming speed on drawability under different friction conditions. By means of deep drawing tests, dry film lubricant and mineral oil lubricant were evaluated for forming the aluminum alloy 5182-O. Different speed profiles under two slide motions were tested in a servo press. Non-isothermal finite element analysis was developed to determine forming parameters for the tests and to investigate more detailed effects of forming speed on the drawing process at room temperature. The comprehensive discussions on material properties, friction and heat generation are provided to help to understand the influence of drawing speed on the practical stamping operations.

2 EXPERIMENTAL PROCEDURES

2.1 Test material and dry film lubricant

Aluminum alloy 5182-O has an extensive application in automotive industry, due to its light weight and good drawability. In the present study, the material properties were characterized by both tensile test and viscous pressure bulge (VPB) test. The tensile test data included 22% uniform elongation, 124 MPa yield stress and 285 MPa ultimate tensile stress. VPB test, developed by CPF, could provide higher strain values under biaxial state of stress [14]. Fig. 1 shows the flow stress curves obtained from the two tests. It can be seen that, with the VPB test, the flow stress could be obtained at true strain about 0.5. In a previous study on Al 5182-O, various lubricants were evaluated using cup drawing test in a hydraulic press. It was shown that dry film lubricant has a better performance during drawing operation [15]. The Al 5182-O blanks (thickness 1.2 mm) used in the present study were pre-coated with dry film lubricant (1±0.3 g/mm^2).

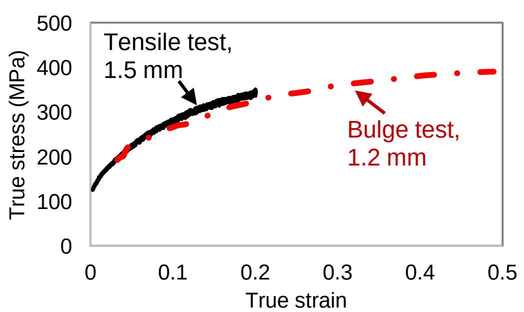


Figure 1: Flow stress curves of Al 5182-O obtained from tensile test and VPB test.

2.2 Illustration of tooling for the deep drawing test

The schematic of the deep drawing tooling is illustrated in Figure 2. This die was originally designed to form advanced high strength steels. The die cavity was assembled by several inserts with different radii and curvilinear shapes. The clearance between punch and die was 1.6 mm. The maximum drawing depth allowable in this die is about 80 mm.

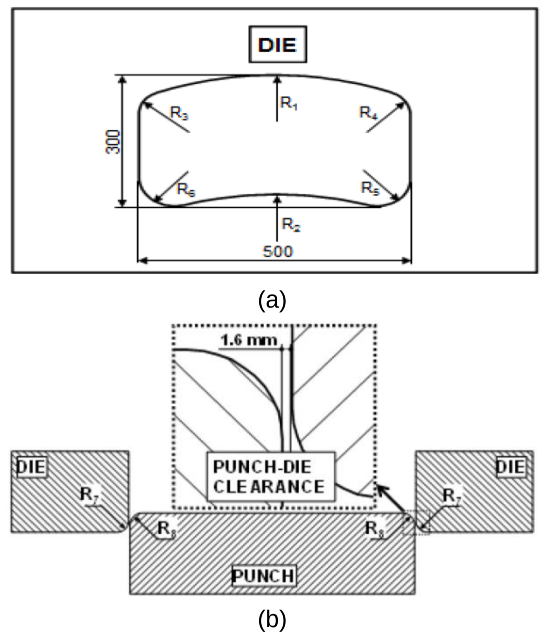


Figure 2: (a) Top and (b) cross-sectional view of deep drawing tooling, dimensions are in mm (R_1=1501.6, R_2=1998.4, R_3=51.6, R_4=55.6, R_5=61.6, R_6=66.6, R_7=20, R_8=10).

2.3 Servo press

In the current experimental study, a 300 ton Aida mechanical servo press with 25 ton CNC cushion was used to conduct the deep drawing tests, as shown in Figure 3. The ram movement can be programmed to several desired profiles. Using the CNC die cushion, the press has the capability to control the forming speed and blank holder force in deep drawing operations. The die cushion force can be varied through the stroke and the maximum value is 25 ton. The press cushion also has the pre-acceleration function, which can be controlled to several states (strong, medium and weak), in order to reduce the impact of the die upon the blank. The data measurement and storing function can record ram positions, speeds, as well as punch and die cushion loads in real time.

Figure 3: Experimental deep drawing tooling assembled in the 300 ton servo press

2.4 Ram speed for the deep drawing test

Two types of speed profiles are analyzed, including 1) mechanical crank motion (1 SPM, 10 SPM and 18 SPM), and 2) constant speed during deformation (50 mm/s and 310 mm/s). As seen in Figure. 4, the mechanical crank motion is a basic sine curve. However, for constant speed profile, the ram speed could not be kept constant during the whole forming stroke, because at a certain stroke position it is necessary for the slide to decelerate to the bottom dead center (BDC).

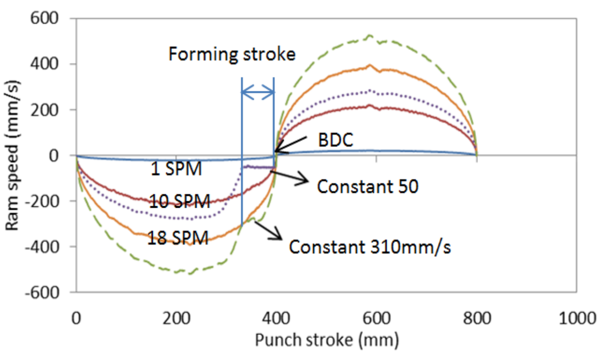


Figure 4: Ram speed profiles with crank motion (1 SPM, 10 SPM and 18 SPM) and constant (50 mm/s and 310 mm/s) during deformation.

Since the ram speed changes during the drawing process, the sheet material deforms at variable strain rates. In round cup drawing, the relationship between effective strain rate at the flange and punch speed can be expressed as Eq. (1) [16]:

$$\dot{\epsilon}_{\text{flg}} = \frac{2}{\sqrt{3}}\left(\frac{r_{punch}}{r^2}\right)\dot{u}_{punch} \quad (1)$$

Where, $\dot{\epsilon}_{\text{flg}}$ is effective strain rate at the flange region; $\dot{u}_{punch}$ represents punch speed; r_{punch} is punch radius; *r* is initial blank radius (in round cup drawing). However, for the rectangular shape punch and sheet used in the current case, the approximate equivalent values were used for the calculation. The dimensions can be obtained from Figure 2.

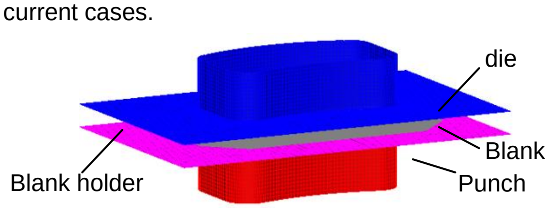
The maximum ram speed 18 strokes per minute (SPM), corresponding to the contact speed of around 310 mm/s, was suggested in the tests (as shown in Figure 4). The average speed during deformation is approximately 10 mm/s when using 1 SPM as the ram speed. Thus, according to Eq.1, the equivalent strain rate range $0.001s^{-1}$ and $0.1s^{-1}$ during the drawing process could be estimated. Although the enhanced formability in Al 5182-O during high strain rate free-forming has been reported, the material properties still exhibited very little sensitivity at quasi-static strain rate range $0.001\sim0.1s^{-1}$ at room temperature [17].

3 FINITE ELEMENT SIMULATIONS

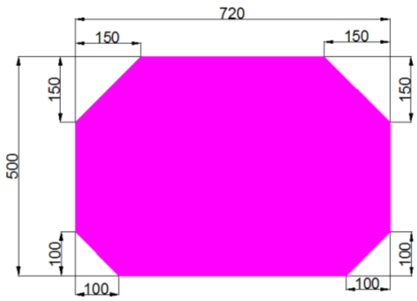
3.1 FE modeling of deep drawing test

The finite element simulations were carried out to design the blank shape and to estimate forming parameters, such as blank holder force and draw depth. Generally, the heat generation, induced by deformation and friction, is neglected in most FE analysis of sheet forming process at room temperature. However, it may affect the material behavior, friction conditions and even the performance of lubricants. To understand the complex interactions between those factors during deep drawing of Al alloys at room temperature, it is necessary to analyze the process using a non-isothermal FE model.

In the current study, a 3D model is built for non-isothermal forming using commercial software PAMSTAMP (Figure 5a). The punch is fixed in the press, while upper die and blank holder move towards the punch. The blanks are designed with rectangular shape with chamfered corners (Figure 5b). In the FE model, 4-node shell element was used to present the deformation and heat transfer behavior of the blank. The mechanical and thermal properties of the sheet material are summarized in Table 1. Based on previous study on lubricant using cup drawing test, the range of coefficient of friction (COF) 0.08~0.12 was selected for dry film lubricant and mineral oil lubricant [15]. In the current FE simulations, the specific COF for each forming condition is determined by minimizing the difference between measured and predicted results, including flange length and punch load. The tools are set as rigid bodies with 6 mm thermal thickness, to enable the calculation of temperature gradient. The initial temperature of blank and tools is 25 °C. Based on previous study on warm drawing of Al 5754 round cups, in order to emulate the effect of contact pressure on the heat transfer coefficient (HTC), the interface HTC of sheet-punch is selected as 5000 $W/m^2 \cdot K$, while 1000 $W/m^2 \cdot K$ is for sheet-die and sheet-blankholder [18]. However, the effects of convection and radiation were negligible in the current cases.



(a)



(b)

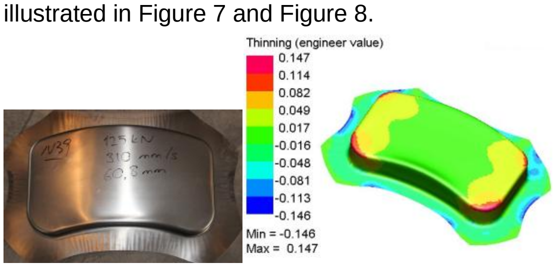
Figure 5: (a) 3D FE model of the deep drawing process; (b) Designed blank dimension (mm)

Table 1: Al 5182-O material properties used in the FE simulations

Property	Description
Flow stress curve	Bulge test data (Fig. 1)
Young's modulus (*E*)	70.6 GPa
Poisson ratio (υ)	0.341
Coefficient of friction (COF)	0.08~0.14
Thermal conductivity (λ)	130 W/m·C
Specific heat capacity (*C*)	900 J/kg·C

3.2 Validation of FE model and determination of forming parameters

Preliminary tests were conducted to set up the 300 ton servo press and validate the FE model developed in PAMSTAMP. As can be seen in Figure 6 (a), the part was successfully drawn to 60.8 mm at 310 mm/s, while the blank holder force (BHF) 125 kN was applied. Figure 6 (b) shows the simulated part in PAMSTAMP. By using COF 0.1, the flange lengths and load stroke curves were predicted and compared with measurements. The comparisons show a good match between experiments and simulated results, as illustrated in Figure 7 and Figure 8.



(a) (b)

Figure 6: (a) Defect free formed part (draw depth 60.8 mm); (b) thinning distribution of simulated part in PAMSTAMP.

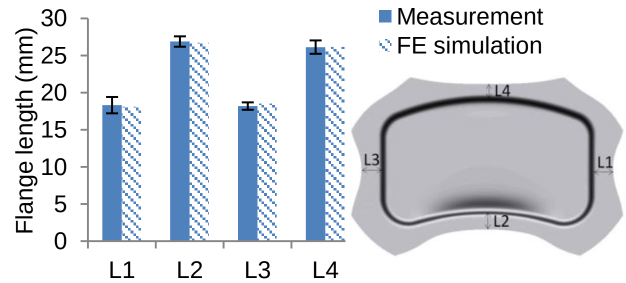


Figure 7: Comparison of flange lengths between experiment and FE simulation (COF 0.1 was applied).

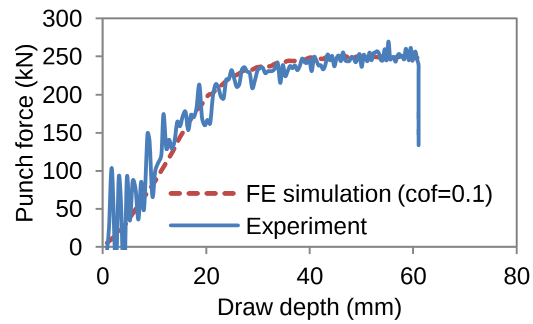


Figure 8: Load-stroke curves from experiment and FE simulation (COF 0.1 was applied).

According to the preliminary tests and FE predictions, the minimum acceptable BHF to prevent heavy wrinkles is 125 kN, which is kept constant during the whole forming stroke. It is found that, under 125 kN BHF, the critical draw depth is 60.8 mm. All tests under same forming condition were repeated three times. In this study, mineral oil lubricant is also used to investigate the effects of lubrication. The test conditions for the deep drawing tests are summarized in Table 2.

Table 2: Process conditions used in deep drawing tests

Conditions	Description
Sheet material	Al 5182-O
Thickness *(t)*	1.2 mm
Testing speed profile	See Figure 4
Blank holder force (BHF)	125 kN (constant)
Lubricant	Dry film lubricant/Mineral Oil
Draw depth *(d)*	60.8 mm (Max. 80 mm)
Cushion pre-acceleration	Medium

4 RESULTS AND DISCUSSION

4.1 Experimental results of deep drawing tests

Figure 9 and Figure 10 present the test results for the samples coated with dry film lubricant. It was found that, the part could be formed without cracks when applying higher crank motion speed (18 SPM), as shown in Figure 9. Due to the convex shape and the smaller corner radius (R_5 shown in Figure 2), the cracks always initially occurred at the right corner and the localized necking was observed at the left corner when using 10 SPM. More severe cracks occurred at both left and right corners when 1 SPM was applied. When using constant speeds during deformation, it also shown that a better drawing quality was obtained at 310 mm/s than at 50 mm/s, as shown in Figure 10.

In order to investigate the effects of lubricant on maximum draw depth under different forming speed, commercial mineral oil lubricant, originally used for AHSS deep drawing, was also tested at 10 SPM and 18 SPM. BHF and pre-acceleration were kept the same as the tests with dry film lubricant. Experimental results showed that draw depth 80mm, which is the maximum allowable stroke for the die, could be successfully achieved without any defect, at both 10 SPM and 18 SPM.

(b)

Figure 9: Results of deep drawing tests with dry film lubricant under different crank motion based forming speeds, stroke 60.8 mm: (a) 10 SPM, crack at right corner and necking at left corner, (b) 18 SPM, defect free formed part

(c)
(d)

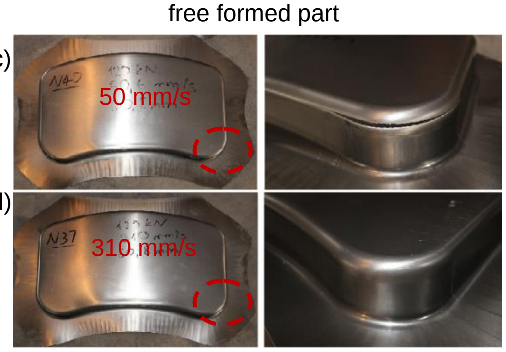


Figure 10: Results of deep drawing tests with dry film lubricant under different constant forming speeds, stroke 60.8 mm: (c) 50 mm/s, crack at right corner, (d) 310 mm/s, defect free formed part

4.2 Comparison of punch load and determination of friction coefficient

It was reported that a sudden decrease of punch load during the forming stroke could roughly indicate the fracture in the failed part. Figure 11 and Figure 12 illustrate the punch load versus stroke with dry film lubricant under the speeds mentioned above. The punch load curves at 10 SPM and 18 SPM are found to be so close as a result of the small difference between their average speeds during deformation. From the results, the load drop could be obviously observed at forming speeds 1 SPM, 10 SPM as well as 50 mm/s. It is seen that the limit draw depths are approximately 52.9 mm, 55.5 mm and 53.6 mm at 1 SPM, 10 SPM and 50 mm/s, respectively. It also can be found from Figure 11 that the maximum punch load is increased by 19 kN when using lower ram speed 1 SPM, while as shown in Figure 12, the increase amounts to 13 kN by using 50 mm/s.

The punch load curves for drawing with mineral oil lubricant are shown in Figure 13. Comparing with using dry film lubricant (Figure 11), the maximum punch load was reduced by around 8% when using oil lubricant in the deep drawing test. Several factors may have affected the drawing results, including 1) the mineral oil was manually applied on the sheet surface while the amount was not precisely controlled; and 2) the punch and die were cleaned with slight mineral oil instead of acetone.

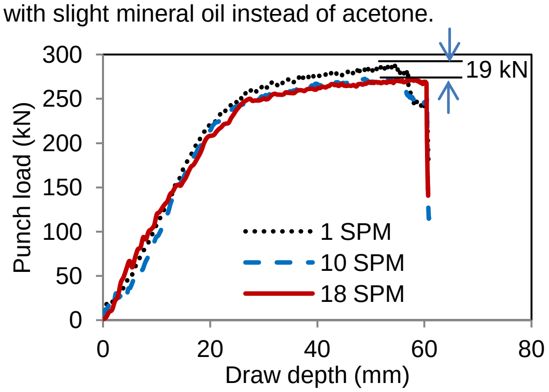


Figure 11: Load-stroke curves at forming speeds 1 SPM, 10 SPM and 18 SPM, with dry film lubricant (BHF 125 kN, stroke 60.8 mm)

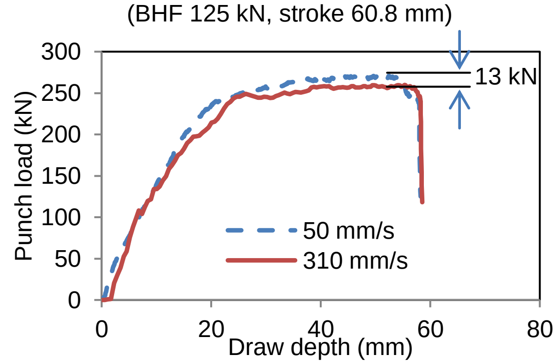


Figure 12: Load-stroke curves at forming speeds 50mm/s and 310mm/s, with dry film lubricant (BHF 125 kN, stroke 60.8 mm)

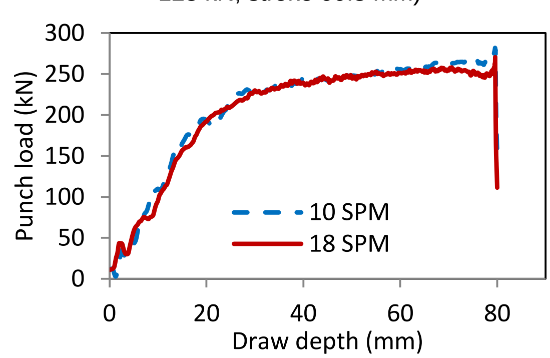


Figure 13: Load-stroke curves at forming speeds 10 SPM and 18 SPM, with oil lubricant (BHF 125 kN, stroke 80 mm)

As mentioned above, by using appropriate COF in simulations, the difference in punch forces between FE predictions and experimental results can be minimized. Based on punch load curves (Figure 11 and Figure 12) recorded during the deep drawing tests, the COF were predicted at ram speed 10 mm/s (approximately average value for 1 SPM), 50 mm/s and 310 mm/s, as shown in Figure 14. In the FE models, the constant drawing speeds during the whole stroke were inputted instead of actual data from the tests. The predicted coefficient of friction was found to decrease with increasing ram speed. Although the static COF was used in the FE analysis of deep drawing process, it could also be concluded that the friction conditions may change with forming speed for dry film lubricant.

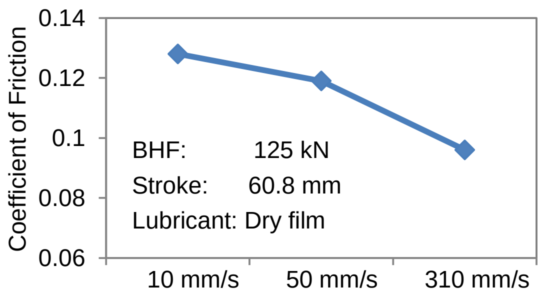


Figure 14: Predicted coefficient of friction at different forming speeds

4.3 Prediction of temperature distribution in the drawn parts

Considering the heat generation during deep drawing process at room temperature, the proposed thermal-mechanical FE model was able to predict the temperature increase in the drawn part. The predicted temperature distribution in the part is as shown in Figure 15. The higher temperature is found round the die-shoulder corners. Based on the predicted COF, friction work is found to change with forming speed, which affects the temperatures at the interface between tool and sheet. Also lower forming speed provide more time for the heat transfer from the drawn part to the cold die. The section A-F (Figure 15) was selected to evaluate the effect of forming speed on the temperature distributions. As illustrated in Figure 16, the maximum temperatures at location E are 77.3 ºC at 310 mm/s, 52 ºC at 50 mm/s and 34.8 ºC at 10mm/s. According to the observations from the drawing tests, the deviation in temperatures on the drawn part was reasonable and not severe to change the performance of the lubricant during the tests.

Regarding the temperature rises in the tools, that the highest temperatures 27 ºC and 32 ºC were predicted in the punch and die, respectively, at forming speed 310 mm/s. The peak temperature in the die occurred at the corner regions. However, it was found that the location of peak temperature in the punch moved from the corner to the wall with forming stroke.

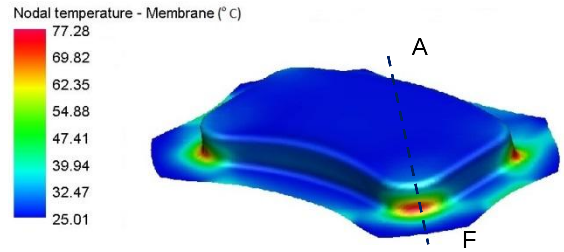


Figure 15: Temperature distribution in the drawn part at forming speed 310 mm/s, stroke = 60 mm

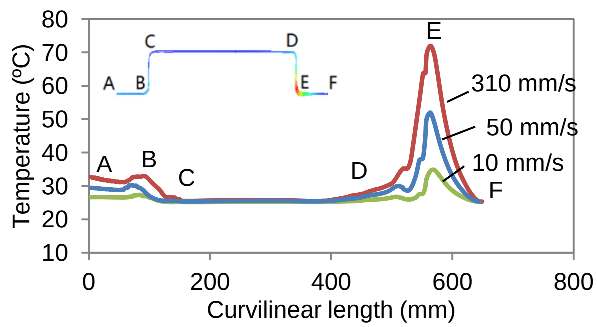


Figure 16: Predicted temperature distributions in the drawn part alone the selected section A-F at different forming speeds, stroke = 60 mm

5 CONCLUSIONS

Deep drawing tests were utilized to investigate the effects of forming speed on drawability of aluminum alloy. The main conclusions are summarized as follows:

1) The tests were conducted in the servo press which can provide controllable slide velocity. The non-isothermal FE model was developed by using commercial software PAMSTAMP to help to determine test parameters and to analyze the drawing process. The model was verified by comparing the predicted and measured flange lengths as well as punch loads.
2) It was found that higher forming speed could help to obtain a deeper draw depth when using dry film lubricant. The ductile fracture process including localized necking could be observed at the part corners during the deep drawing. The comparisons between experimental load stroke curves demonstrated that the punch load was reduced by using a higher forming speed. The friction coefficient, determined by matching the punch forces between predicted and experimental results, decreased with increasing forming speed. It could be concluded that the variable frictional behavior during deformation was the main reason for the forming speed effects.
3) Regarding the heat generation during deformation, the peak temperature 77.24 ºC in the drawn parts was predicted under forming speed 310 mm/s and it was found that there

were only slight temperature rises in the tools. The results of heat generation were evaluated to have no significant effects on the drawing process for only single stroke operation.

6 ACKNOWLEDGEMENTS

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