Key Engineering Materials
ISSN: 1662-9795, Vol. 926, pp 1195-1203
doi:10.4028/p-qh2392

Submitted: 2021-12-13
Revised: 2022-01-28
Accepted: 2022-02-01
Online: 2022-07-22

Performance Evaluation of Lubricants with Swift Cup Drawing

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Keywords: friction, lubricants, Swift cup drawing test, stamping, AA5182, mechanical model.

Abstract. The quality of a part produced using stamping process is dependent on many parameters such as the geometries of the tools and the initial blank, their surface state, the clamping force or contact pressure, the tools velocity and the lubrication. In order to discriminate different lubricants for stamping process in automotive industry under various conditions of clamping force and punch velocity, the Swift cup drawing test is used to evaluate the performance of three lubricants, i.e., two oil-based liquids and one dry film, applied on AA5182-O sheets. Moreover, finite element simulations are used to estimate friction coefficients of these lubricants.

Introduction

The effectiveness of a stamping process is dependent on many parameters such as the tool geometries, the blank shape, the mechanical behavior of the material to form, the clamping force, the tools velocity, the surface state of the tools [1] and the lubrication. In order to reduce the weight of automotive parts and therefore greenhouse gas emissions, the use of aluminum alloys is an interesting solution. However, the use of aluminum alloy sheets can lead to high adhesion which leads to failure of automotive parts [2]. Thus, the use of lubricants to reduce friction is necessary [3]. The lubrication effectiveness is dependent on the lubricant used, hence the importance of evaluating the performance of different lubricants.

Prakash V. and Kumar D. R. [4] evaluate the effectiveness of different bio-lubricants using deep drawing tests and determinate their corresponding friction coefficient using strip drawing tests. They show that the bio-lubricants can replace the mineral-oil-based lubricant at low pressure, but at high pressure, the friction coefficients of these bio-lubricants increase contrary to the friction coefficient of the mineral-oil-based lubricant which remains stable. To evaluate the effectiveness of different benign lubricants, Wieckowski & al [5] used the strip drawing and Erichsen cupping tests, and an industrial process for surgical tools. They showed that the addition of boric acid into oil-based lubricants decrease the friction coefficient. The effect of nanoparticle additives of Al_2O_3 was studied by Zareh-Desari & al [6]. In their work, cylindrical cup drawing test was used to evaluate the effectiveness of nanoparticle additives with different concentrations in a based oil lubricant. Based on the criteria of maximum punch force and surface quality, the adding of nanoparticles (which doesn't exceed 0.6wt.%) lead to a better lubrication. An estimation of the friction coefficients was also performed using a FE-based iterative algorithm. In the work of Kim & al [7], a cylindrical cup drawing test device is used to evaluate performance of five lubricants based on criteria such as maximum punch force, the maximum applicable blank holder force, the draw-in length, the change of surface roughness. Moreover, they determined the friction coefficient for each lubricant using a finite element (FE)-based inverse analysis with the software PAM-STAMP. To determine the friction coefficient of dry or lubricant tests of the cylindrical cup drawing, Folle and Schaeffer [8] used a FE model through Dynaform and showed that the experimental and numerical results are generally in agreement.

The work presented here was made in the context of the AM2 collaborative project led by the automotive manufacturer Stellantis. The goal of this study is to present a method to discriminate different lubricants in order to guide the lubricant choice in the industrial process of stamping. Three lubricants are evaluated using the cylindrical cup drawing test. Two lubricants are oil-based liquids commonly used in stamping process and the third is a dry film which should have better performance as described in [9]. The performance of the three lubricants are evaluated based on the following criteria:

- The maximum punch force attained
- The repeatability of the results
- The thickness of the cup

Moreover, the friction coefficients corresponding to the use of these lubricants are determined using mechanical FE simulations performed with the software Abaqus/Standard.

Method

Material. AA5182-O aluminum alloy sheet with a thickness of 0.9 mm is considered in this work. Its mechanical properties are described in Table 1 and come from tensile tests performed on an Instron 5969 tensile machine. The Young's modulus E, the yield stress YS and the Ultimate Tensile Strength UTS are given from tensile tests performed in rolling direction. The normal anisotropy coefficient is lower than 1 and the planar anisotropy coefficient is weak.

Table 1: Mechanical properties of AA5182-0.

E (GPa)	YS (MPa)	UTS (MPa)	r_0	r_{45}	r_{90}	$\bar{r}$	Δr
72	152	293	0.638	0.716	0.666	0.684	-0.064

For a first approach in this study, the anisotropy is neglected in the FE simulation. Isotropic hardening with von Mises yield criterion is chosen to model the mechanical behavior of this metal. The yield function is given by:

$$f = \bar{\sigma} - \sigma_y(\bar{\varepsilon}_P) \tag{1}$$

where $\bar{\sigma}$ is the von Mises equivalent stress that is defined as follows:

$$\bar{\sigma} = \frac{1}{\sqrt{2}}\sqrt{(\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2} \tag{2}$$

where σ_I, σ_{II} and σ_{III} are the principal stresses.

$\sigma_y(\bar{\varepsilon}_P)$ denotes the isotropic hardening function that is chosen with a Swift equation:

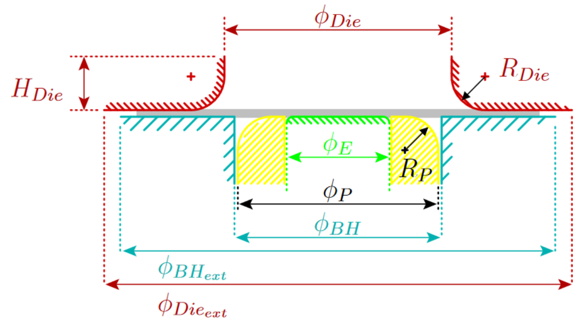
$$\sigma_y = K\left(1 + \frac{\bar{\varepsilon}_P}{\varepsilon_0}\right)^n \tag{3}$$

where $\bar{\varepsilon}_P$ is the equivalent plastic strain and K, ε_0 and n are the material parameters. These parameters are identified based on the experimental stress-strain curve obtained from a tensile test performed in rolling direction. The obtained values are K=150 MPa, $\varepsilon_0 = 0.011$ and n = 0.3. The Poisson's ratio ν is set equal to 0.33.

Experimental approach. The cylindrical cup drawing tests (Swift tests) were performed on a Zwick/Roell Amsler BUP 200 sheet metal testing machine. The basic diagram of the test procedure is presented in Fig. 1.a. The Swift test consists of clamping a circular blank on its perimeter and drawing the blank with a cylindrical punch until a cup is obtained. The AA5182-O sheets were cut into circular blanks of 60 mm diameter with the cutting tool of the BUP 200 machine.

The dimensions of the Swift test tools are given in Fig. 1.b. The inner diameter of the die is $\Phi_{\text{Die}} = 35.25$ mm and the outer diameter of the punch is $\Phi_{\text{P}} = 33$ mm, leading to a gap between the die and the punch of 1.125 mm. The radius of the die and the punch is 5 mm. Two clamping forces of 6 and 12 kN and two punch velocities of 1 and 13 mm.s^{-1} are tested in this study.

a)



Tool Dimensions [mm]

ϕ_{Die}	R_{Die}	H_{Die}	ϕ_P	R_P
35,25 *	5	8,75	33	5

ϕ_{BH}	$\phi_{BH_{ext}}$	$\phi_{Die_{ext}}$	ϕ_E
33,6	70	80	20

* : theorical value, the measure gives 35,30 mm

b)

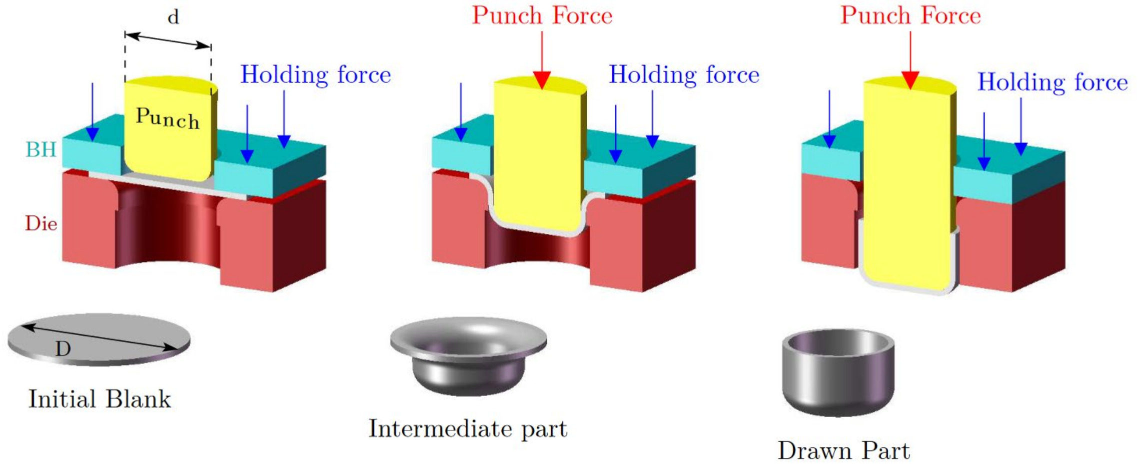


Fig. 1: a) Basic diagram of the Swift cup drawing test and b) tools dimensions used for the Swift cup drawing tests [10].

Among the three lubricants evaluated, two were oil-based liquids and the last a dry film, respectively named lub(a), lub(b) and lub(c) in the following. The AA5182-O sheets of 0.90 mm thickness with the dry film (lub(c)) of 1 g.m^{-2} were provided by Constellium. The two oil-based liquids (lub(a) and lub(b)) were applied on these sheets after a washing using alcoholic solutions. To ensure a uniform lubrication, a cotton cloth was used to spread these lubricants. The control of the mass of oil applied was carried out by a double weighing method, giving results ranging from 1.10 to 1.15 g.m^{-2} for lub(a) and from 0.81 to 1.15 g.m^{-2} for lub(b). The typical amount of lubricant applied by Stellantis during the aluminum forming stages is between 1.00 and 2.00 g.m^{-2}.

To evaluate the performance of these lubricants and create a ranking, the following criteria are used:

- The maximum punch force attained (higher is the punch force attained, lower is the performance)
- The repeatability of the results (better is the repeatability, better is the performance)
- The thickness of the cup (lower is the thickness reduction, better is the performance)

Numerical approach. Numerical simulations of the Swift cup drawing test are performed with the FE code Abaqus/Standard. A 2D axisymmetric model is adopted since the geometry of the tools, the workpiece and the loading are axisymmetric and also the metal sheet is assumed to be isotropic. Geometries of all parts in the simulation are set according to the experimental setup as shown in Fig.2. The workpiece is modelled as a deformable body with an elastic-plastic material using the material properties specified previously. Structured 4-nodes bilinear axisymmetric quadrilateral elements with reduced integration (CAX4R) are used to mesh the workpiece with a mesh size of 0.1 mm. The tools are modelled as deformable bodies with an elastic material (E = 215 GPa and ν = 0.3). CAX4R elements and 3-nodes linear axisymmetric triangle elements (CAX3) are used to mesh the tools. A fine mesh is applied in the contact area while a large one is used away from this zone. The total number of elements used to mesh the workpiece and the tools is 12070. Coulomb's friction law is used to solve the frictional effect of the tool-workpiece interfaces with a friction coefficient f_c. Numerical simulation is performed in two steps. In the first one, a blank-holding force F_{BH} is applied to the blank-holder. Then the punch is constrained to move in the axial direction. It should be noted that the tools are not removed after forming since springback phenomenon is not considered in this work.

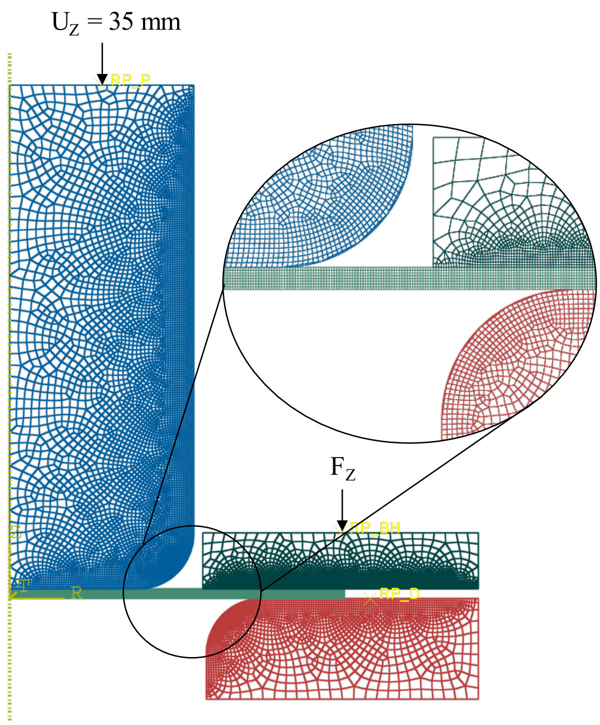


Fig. 2: FE model of the Swift cup drawing test.

Results and Discussion

Performance evaluation of lubricants. As explained previously, the performance of the three lubricants is evaluated for different process parameters. The repeatability of the results is shown in Fig. 3 with four tests performed for each lubricant. The gap between the different curves corresponding to lub(a) is higher than the one recorded for the two other lubricants. Given the variations of the results with lub(a), an average curve was calculated for lub(a) in order to compare this lubricant to the others in the following. Nevertheless, the dispersion in the punch force for lub(a) will also be presented in the following figures. Between lub(b) and lub(c), there is a better repeatability for lub(c) after 21 mm punch displacement. Better is the repeatability, better will be the stability of the forming process.

Fig. 4 shows the influence of the clamping forces and punch velocities on the punch forces during Swift tests with lub(a). The presented curves are average curves for lub(a) with their dispersion, even for a clamping force of 12 kN and a punch velocity of 13 $mm.s^{-1}$ where the dispersion is very low. As expected, the higher is the clamping force, the higher is the maximum punch force. The peak at 16 mm punch displacement for the punch force of 12 kN and a punch velocity of 1 $mm.s^{-1}$ can indicate the presence of galling [8] which is a criterion of failure. Regarding the influence of speed, the higher it is, the lower is the force required to draw the cup and the lower is the force dispersion. Which can suggest that the friction coefficient decreases with the increase of the sliding velocity between tools and blank, in case of absence of a strain rate dependency. The same tendencies were observed for the lub(b) and the lub(c) for the influence of the clamping force and the punch velocity.

The difference in the maximum punch force needed for the different lubricants during Swift tests is shown in Fig. 5 for a clamping force of a) 6 kN and b) 12 kN. The maximum punch force decreases respectively with the use of the lubricants lub(a), lub(b) and lub(c).

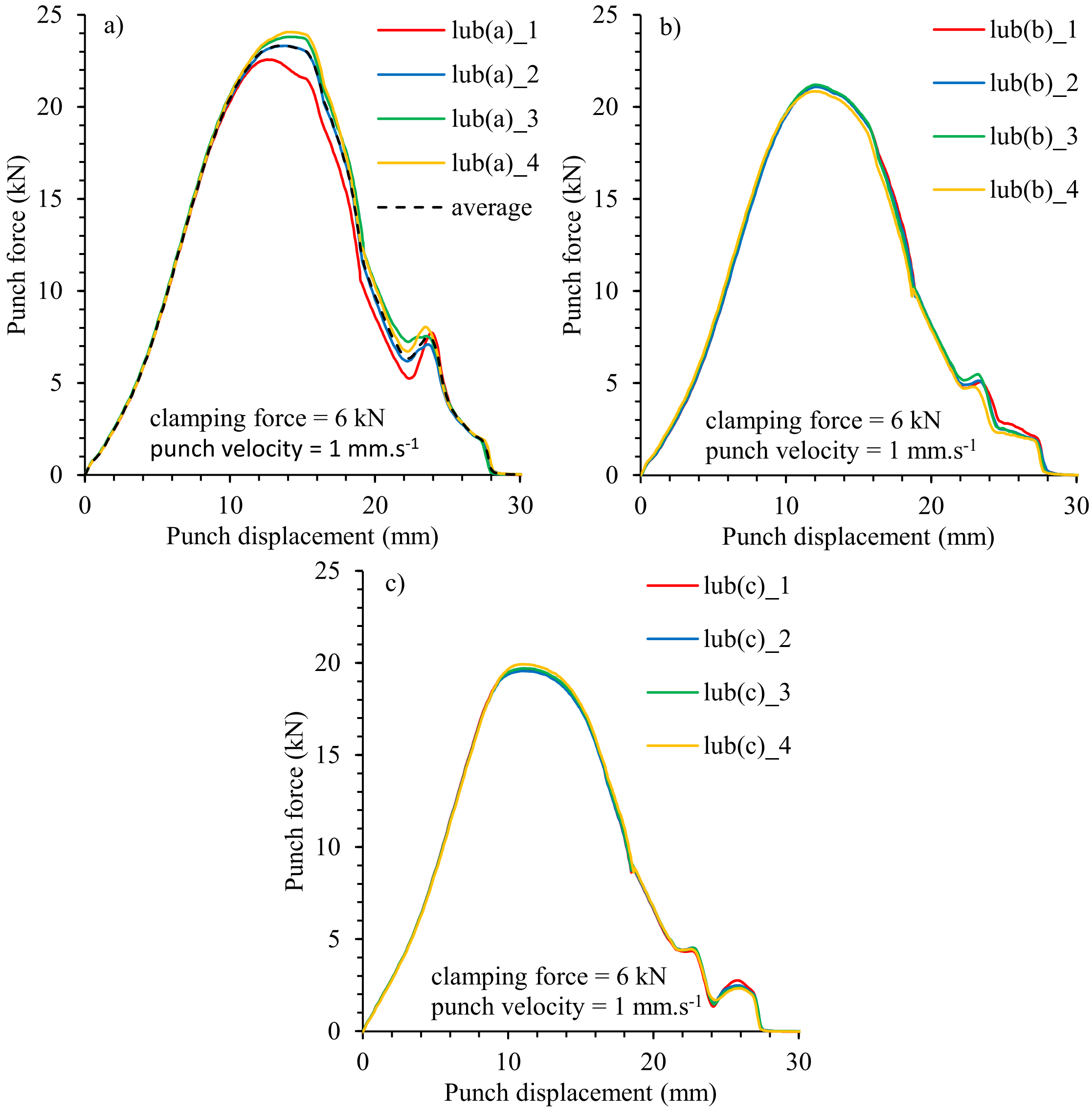


Fig. 3: Highlight of repeatability through punch force as a function of the punch displacement for a clamping force of 6 kN, respectively for the three lubricants).

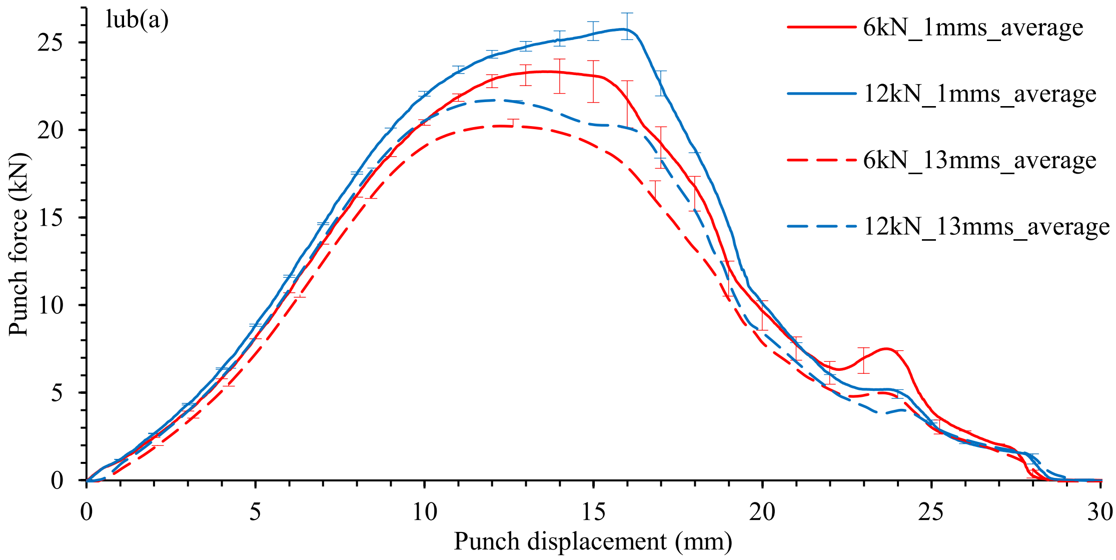


Fig. 4: Punch force average and its dispersion as a function of punch displacement for lub(a), with clamping forces of 6 and 12 kN, and punch velocities of 1 and 13 mm.s^{-1}.

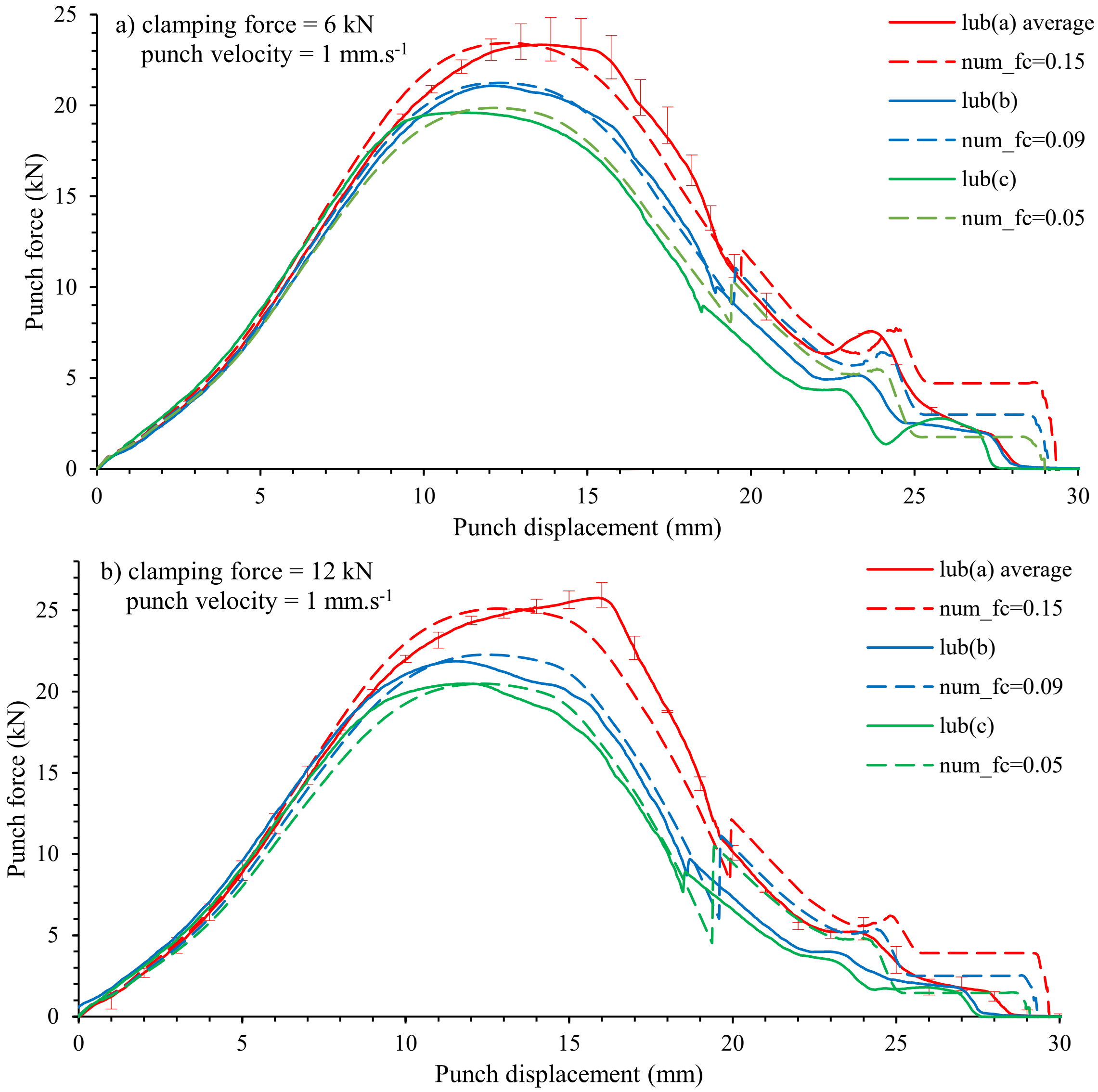


Fig. 5: Comparison between experimental and simulated punch force evolution as a function of punch displacement for the three lubricants, with a punch velocity of 1 mm.s^{-1} and clamping forces of a) 6 kN and b) 12 kN.

The last criterion used to evaluate the lubricant performances is the thickness of the cup. As shown in Fig. 6 for a clamping force of respectively a) 6 kN and b) 12 kN, the reduction of thickness is higher using lub(a) than using lub(b) and is higher using lub(b) than using lub(c).

For all the criteria used in this work, the lubricant ranking is the same, i.e., the better lubricant is lub(c), then lub(b) and finally lub(a).

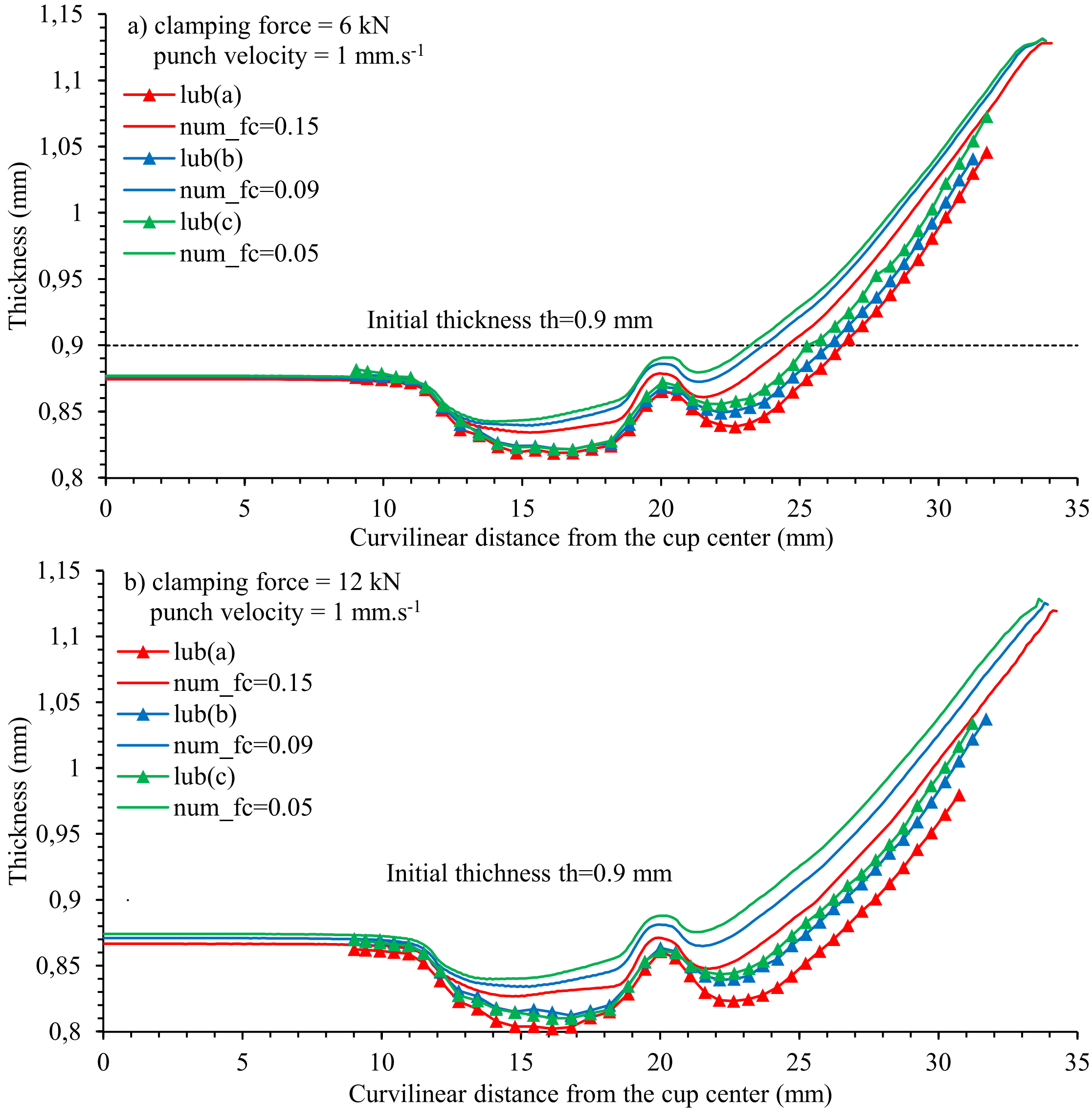


Fig. 6: Cup thickness evolution as a function of curvilinear distance from the cup center: experimental and numerical results.

Friction coefficients estimation. The friction coefficient for each lubricant is identified by an inverse method that consists of manually adjusting the unknown parameter while visually checking the agreement between experimental and numerical results. Indeed, the friction coefficient is continually adjusted until the numerical and experimental punch force-displacement curves obtained for a clamping force of 6 kN show good agreement as shown in Fig. 5.a. The optimal value of f_c for each lubricant is given in Tab.1, except for lub(a) where a range of values is also given due to the dispersion of results.

Table 1. Friction coefficients identified for each lubricant for a clamping force of 6 kN.

Lubricant	*Lub(a)*	*Lub(b)*	*Lub(c)*
Friction coefficient f_c	0.15 [0.12 - 0.17]	0.09	0.05

It can be seen that the shape of the numerical and experimental curves is similar. However, numerical results overestimate the experimental punch load in some areas of the curve and underestimate it in others. In terms of the maximum punch load, a good agreement between numerical and experimental results is observed.

Fig. 5.b shows the comparison between the punch force-displacement curves obtained experimentally and numerically for a clamping force of 12 kN with the same friction coefficients identified previously (i.e., for a clamping force of 6 kN). A good agreement between numerical and experimental results is also observed, especially for lubricants lub(b) and lub(c) indicating a weak dependency of the friction coefficient to the contact pressure.

To further validate the identified values of friction coefficients, the numerical distribution of the thickness in the cup wall is superimposed in Fig. 6. It can be seen that the overall shape of the experimental and numerical curves is similar. Numerical results overestimate the experimental thickness with a difference that does not exceed 6 %. This slight discrepancy can be attributed to the use of the isotropic yield criterion to accurately model the through-thickness deformation, for this metal exhibits a through-thickness anisotropy, i.e., $\bar{r} = 0.684$. This could be improved by using an anisotropic yield criterion. It is also found that, as the friction coefficient increases, the thickness of the wall decreases in the same trend as the experimental results.

Conclusion

The swift cup drawing test is able to discriminate different lubricants through the following criteria, the maximum punch force or drawing force, the tests repeatability and the reduction of thickness. In this study lub(c) is the best lubricant, as expected for a dry lubricant compared to commonly oil-based lubricants used in stamping process.

The presented numerical model leads to a good agreement between experimental and numerical results in terms of punch forces and thickness reductions. The friction coefficient value identified for each lubricant confirms the lubricant ranking from the experimental results.

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