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# Tribology of forward extrusion – from the identification of friction to the prediction of abrasive and adhesive wear

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## Abstract

The tribology of cold forward extrusion is studied on the bases of a process centered approach. The process centered approach involves a test bench designed specifically to simulate the conditions of contact encountered in industrial cold forming process, industrial tool as contactor and industrial workpiece as specimen. The approach is applied to study various aspects of forward extrusion: choice of lubricants, wear of WC die, galling of aluminum alloys.

**Keywords :** Tribology, Process centered approach, Forward extrusion, WC die, Aluminum alloy, Steel.

## 1. Introduction

The term “precision forging” describes a philosophical approach to forging, which aim is to produce a net shape, or a near-net shape. Cold-forging processes are traditionally precision processes. Within the cold forging processes, forward extrusion is a common process, able to produce a large range of preform. In forward extrusion, a punch applies pressure to a billet, causing the work metal to flow through a die. The contact pressure between the billet the extrusion tools range from 34.5 MPa for soft metals, up to 3 GPa for alloy steel [1]. These extreme conditions of contact require efficient lubrication in order to limit tool wear. Indeed, the costs of the tools may constitute even 8–15% of the total production costs. In extreme cases, with small production series, it can even reach 30% [2]. In addition to the cost aspects, tool wear significantly decreases the quality of the produced forgings. A worn tool leads to incomplete forging (lapses in the filling of the die impression), overlaps, flashes, scratches, delamination, micro and macro cracks, etc. Therefore, controlling the lubrication process is a key point to manage tool wear and, consequently, to increase tool life and reduce production cost.

In the present paper, a process centered approach of the tribology of metal forming is presented. This approach aims to identify reliable coefficient of friction. It involves friction benches specifically designed to simulate the contact conditions encountered in cold metal forming. The approach is first involved to choose a lubricant for a forward extrusion process of mild steel, and second to analyze wear modes at the extrusion die/billet interface. Finally, a numerical strategy is presented to predict galling in cold extrusion of aluminum alloys. The numerical strategy uses coefficients of friction identify from the process centered approach.

## 2. Tribology in metal forming: a process centered approach.

Friction depends on many physical, chemical and mechanical parameters: stresses, strains, surface enlargement, hardness or bulk yield stress, roughness parameters such as skewness or kurtosis, tools and billet temperatures, sliding velocities, chemical properties of lubricants, lubricant film thickness, etc. It is not possible to reproduce all of them with a single tribological test and, consequently, to analyze the effect of all these parameters on the efficiency of a lubricant. The idea is then to dissociate the mechanical parameters from the physical-chemical parameters. The test bench is designed in order to easily adjust the contact pressure, plastic strain and sliding velocity on the test bench to those of the studied process. The reproduction of extrusion physical and chemical parameters are ensure by using specimens and contactors directly machined from industrial parts and tools. This lead to a testing methodology that operates in four steps (Figure 1). First, the magnitude of key process parameters are evaluated. For cold forming, the key parameters are sliding velocities, tool and workpiece temperatures, contact pressure, plastic strain and surface enlargement [3]. Second, specimens and contactors are machined from industrial parts and tools. Materials used on the test bench and on the process are then identical: same roughness, chemical reactivity, oxidation, hardness, etc. Third, the test bench loading is adjusted in order to simulate the key parameters evaluated at step 1. Consequently, the design of the friction test have to

allow an independent adjustment of temperature, sliding velocity, strain and stress [4]. Fourth, tests are performed and results are analyzed to provide quantitative and qualitative information on the process lubrication [3]. Tests results allow the identification of coefficients of friction related to various friction models to quantify the ability of lubricants to reduce friction [5], and surface analyses, such as EDS, EBDS, surface roughness, to qualify the efficiency of lubricants to protect the tool and parts surface [6].

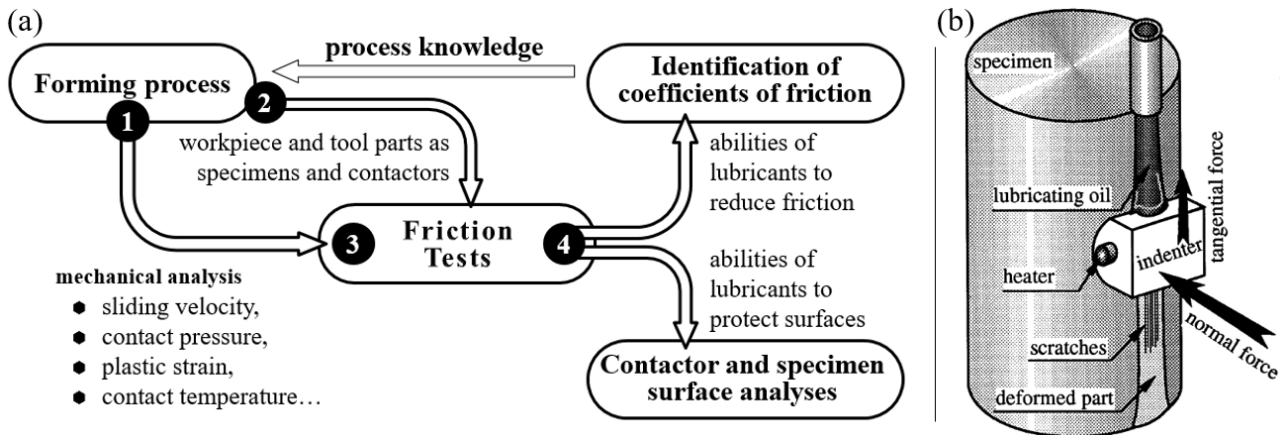


Fig. 1. (a) Process centered approach to simulate industrial conditions of contact with a laboratory friction test [3], (b) schematic view of the Upsetting Sliding Test.

### 3. Forward extrusion: identification of coefficient of friction at the wire/extrusion die interface.

The process centered approach is applied to study a forward extrusion process of a steel billet [6]. The reduction equals 75% in area. The billet is sheared from a wire with zinc phosphate coating. A finite element analysis of the forming process shows that the sheared face of the billet interacts with the die at about the half of the reduction zone (Fig. 2). A liquid lubricant is then required to avoid direct metal-to-metal contact that would result in an increase of friction and tool wear. From the FEA, it comes that the contact pressure in that area equals 2.2 GPa and that the sliding speed is very low since a small dead zone can be formed. The temperature at the billet/die interface is estimated between 25°C when the process starts, and 150°C in the process is running.

A set of experiment is performed in order to select oils that could be used in addition to the zinc phosphate coating. Tests are performed on the Upsetting-Sliding Test (UST) [4]. The UST involves a contactor, a specimen with a straight surface, and a supply of lubricant (Fig.1b). The contactor applies a given pressure on the specimen surface and slides against its surface where it creates a plastic strain. Lubricant is applied at the contactor/specimen interface. In order to respect the physical parameters of the extrusion process, the indenter is made in the same material as the die, with the same manufacturing process. A particular attention is paid to the respect of surface roughness. On the other hand, 42 mm long specimens are machined from the steel wire used for the billets. A heating cartridge is inserted into the contactor to adjust of the indenter surface temperature within the range of 25–150°C. Seven lubricants are tested: a vegetal oil (HV), a mineral oil without EP additive (HGF), an emulsion of mineral oil in water (HC), and 4 mineral oils with different concentration of chlorine and phosphorus compounds (HEP1 to HEP4). Two main results are analysed: the Coulomb's coefficient of friction  $\mu$ , obtained from normal and tangential forces recording during the test [7], and the sliding length before the first scratch occurs along the sliding track  $L_s$ , measured after the tests (Fig.3). The seven lubricants present the same behaviour at 25°C: the coefficients of friction are in the range 0.23-0.26, and the sliding lengths before scratch  $L_s$  are equalled to the total length of the specimen, meaning that no surface damage is observed along the sliding track. For tests performed at 75°C, the coefficients of friction are slightly increasing for all lubricant but those with a content of chlorine larger than 500 ppm (HEP1 and HEP4). Scratches are observed whatever the lubricant, even for the lubricant with EP additive.  $L_s$  for the mineral oil and the HEP2 lubricant are very closed although HEP2 is a lubricant with high contents of phosphorous and zinc compounds (>2000 ppm). Scratches occurs after 8 mm of sliding, meaning that these lubricants could be used at 75°C temperature only if the extruded part is lower than 8 mm. At 150°C the coefficient of friction for mineral oil et emulsion of oil in water reach very high friction values (larger than 0.5). The coefficients of friction for the lubricants with EP additives remains in a high but acceptable range of 0.3 to 0.36. Nonetheless, scratches occurs after 4 to 7 mm of sliding for all lubricants but HEP4. In conclusion, these results shows that there is no direct

correlation between friction and the protection of surface integrity. Lubricant HEP2 leads to a low coefficient of friction but can hardly protect the surface from scratches. Second, these results highlight the importance of testing lubricant according to the industrial conditions of contact. Performing tests at room temperature for a cold forming process, ignoring the real temperature at the tool/part interface, would lead to the erroneous conclusion that all lubricants are equivalent.

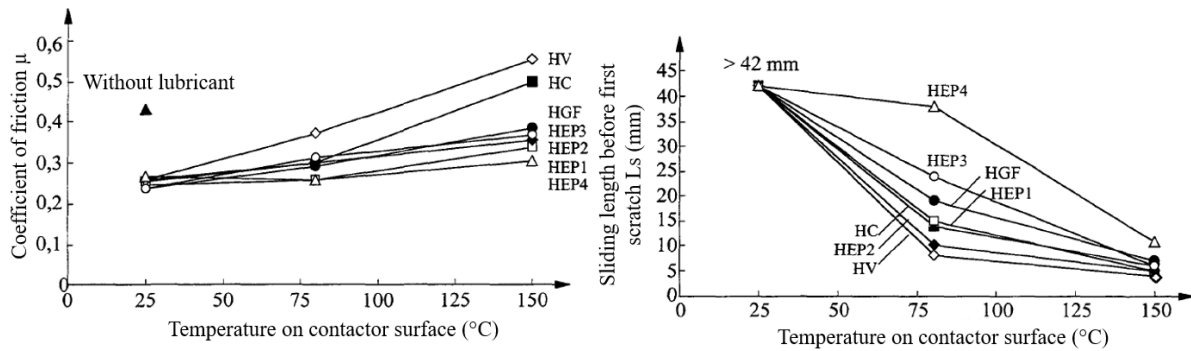


Fig. 2. Coefficients of friction and sliding length before first scratch vs temperature

#### 4. Forward extrusion of steel: wear modes of WC extrusion die

The process centered approach is used to investigate wear modes of WC dies used in forward extrusion. The study focusses on the evolution of WC grain size and morphology with the number of produced parts, and its influence on friction [8]. Four dies are taken from the production line. They have respectively produced 0 (production time  $t_0$ ), 100 000 ( $t_1$ ), 150 000 ( $t_2$ ) and 220 000 ( $t_3$ ) parts. 3D roughness measurements and SEM micrographs are performed along the reduction and the calibration areas of the dies. These surface analyses exhibit that WC grains are subject to plastic strain, grain fracture, and grain removal, leaving room for adhesive wear to take place (Fig. 3). Figure 4 presents the evolution of WC free area along the die for the production times  $t_0$  to  $t_3$ . The abscissa X gives the sizes of the WC free areas in  $\mu\text{m}^2$ , the ordinate Y gives to the localization along the contact zone, and the color of the dots indicates the percentage of WC free area of size X located at position Y. The dash line indicates the limit between the calibration and the reduction zones of the die. New die presents a surface with a homogeneous repartition of small WC free areas (lower than  $1\mu\text{m}^2$ ). The size of WC free areas strongly increases during the manufacturing of the first 100000 parts ( $t_1$ ), notably the reduction zone where they reach values larger than  $6\mu\text{m}^2$ . After 150000 parts ( $t_2$ ), the free areas become smaller along the reduction area, at start increasing along the calibration zone. Finally, after 220000 parts ( $t_3$ ), both calibration and junction zones are covered with large WC free areas (sample D). These analyses show that large grains are fractured to smaller ones. The new small grains are in contact with each other but are not strongly embedded in the cobalt matrix. As a consequence they are easily removed from the surface by the friction stress, leading to the increase of WC free area and the decrease of the small grain population. This phenomena takes place along the reduction area first, and along the calibration area second. Finally, materials transfer occurs in the areas where the WC grains have been removed (Fig.3c).

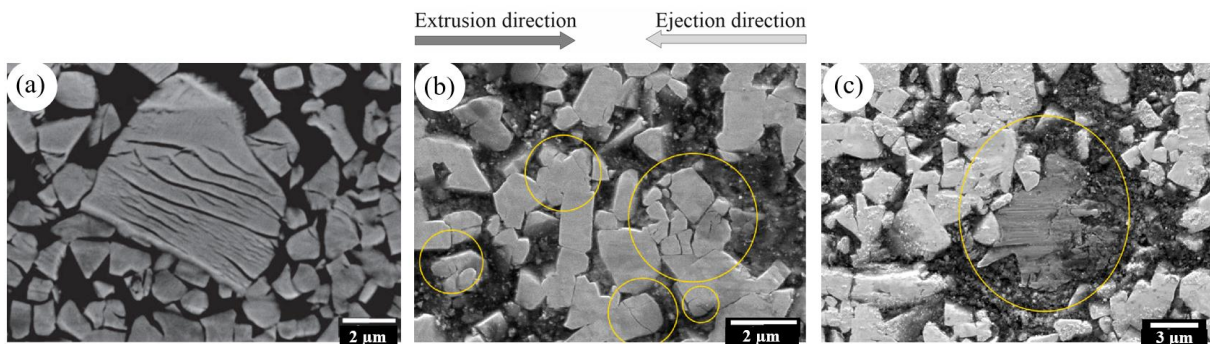


Fig. 3. SEM micrographs. (a) Deformed WC grain at  $t_2$  in the die reduction area. (b) Fractured WC grain at  $t_4$  in the die calibration area. (c) Adhesive wear in a zone subject of grain removal at  $t_1$  in the die calibration area.

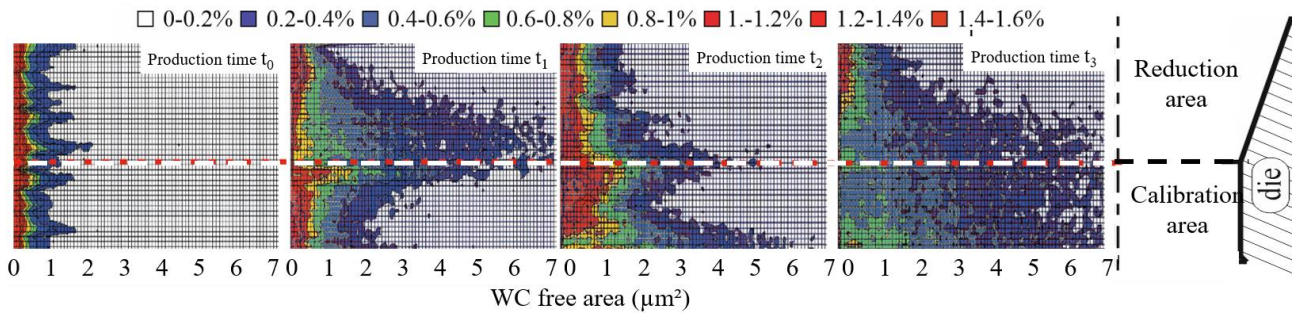


Fig. 4. Distribution of WC free area along the die surfaces for production times between 0 and 220,000 formed parts.

In order to quantify the effect of grain removal and adhesive wear on friction, contactors are machined from the production dies and UST are performed (Fig. 5a). The UST parameters are adjusted to simulate the contact pressure, effective strain and sliding velocity encountered at the die/billet interface, according to Figure 1a. As the number of produced parts increase, the Coulomb's coefficient of friction increases (Fig. 5b), reflect of the surface damage occurring during production. The mean friction coefficient remains lower than 0.12, which can be acceptable for this kind of process. Nonetheless, the tangential stress on die surface increases by 100% during the die life. Consequently, a manufacturer who wants to calculate the stress state in his tooling has to take into account the variation of the coefficient of friction with production. A coefficient of friction identified on a new tool surface would underestimate the real stress distribution.

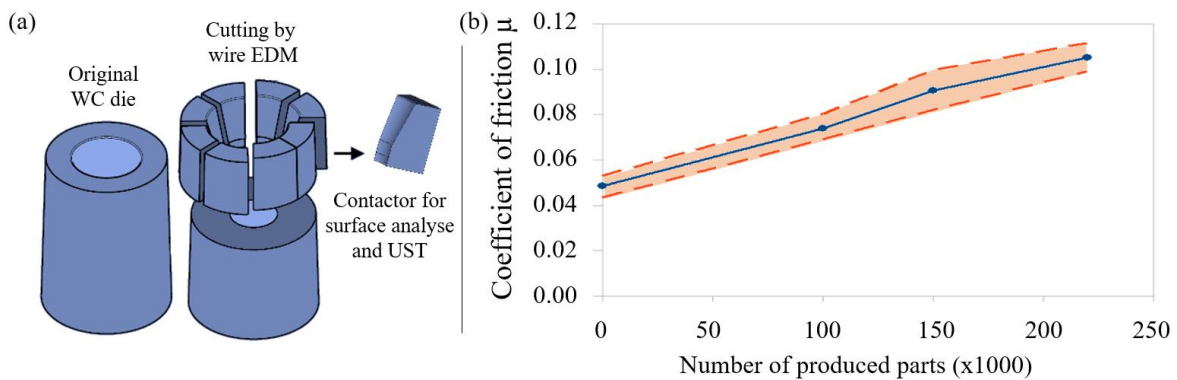


Fig. 5. (a) Geometry of extrusion die and UST contactors. (b) Coefficients of friction vs number of extruded parts.

## 5. Forward extrusion of aluminum alloys – numerical prediction of galling onset

Galling phenomena between the die and workpiece is a severe wear mode leading to a sharp increase in the forming load, material transfer from the soft to the hard surface, fatal damage of the product surface, and severe adhesive wear of the tools [9]. Experiment show that the galling of aluminum alloys (AA) is very sensitive to the roughness of the tool, the stress distribution in the near surface and the lubrication. A numerical methodology has been developed in order to predict the occurrence of galling [10]. The strategy is based on the coupling of a damage and a lubrication model. The lubrication model estimates the stress state in the contact area. The damage model predict if the stress state will lead to critical damage. If critical damage is attained, material can detach from the surface and galling starts. The present methodology uses the lubrication model proposed by WRD Wilson [11]. The main advantage of that model is it provides an accurate estimation of the friction stress based on contact pressure, tool roughness (mean height and angle) and lubricant properties. The damage model involved is the model proposed by Xue [12]. This model depends on the hydrostatic stress and on the Lode angle. Consequently, it implicitly takes into account shear stresses, i.e. friction stress on finite elements near the surface, in the evaluation of the damage variable (Fig. 6). This numerical methodology has succeed in predicting galling according to various conditions of contact and lubrication [13].

In the present work, the methodology is involved to study galling taking place during the forward extrusion of a AA6082 billet with a 45% reduction is studied (Fig. 7). The aim of the study is to tendency of which step of the extrusion process, extrusion or ejection, leads to galling. Three configurations are tested: dry extrusion with a tool/billet equivalent quadratic mean roughness of 0.2 and 4  $\mu\text{m}$ , and lubricated extrusion with a tool/billet equivalent quadratic mean roughness of 0.2. All billets exhibit surface damage, with scratches and flakes (Fig. 8-a,b,c).

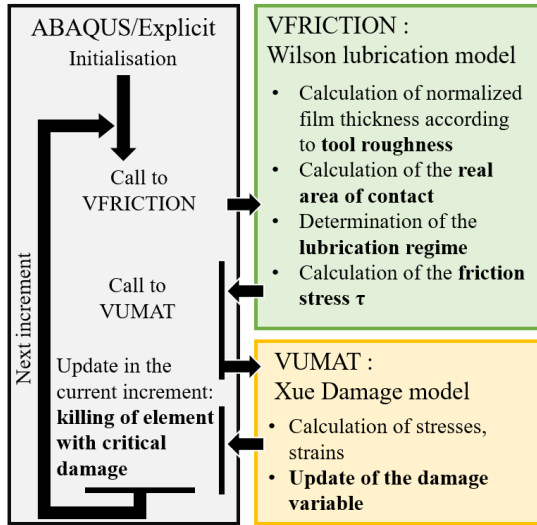


Fig. 6. schematic view of the numerical strategy to predict galling onset, from [Fil24]

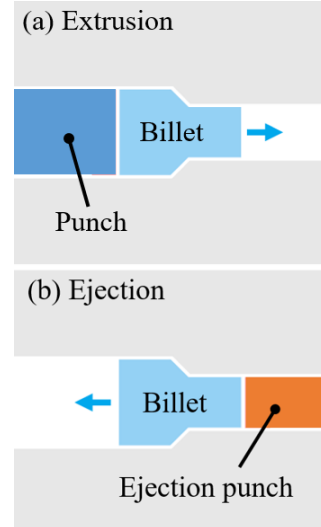


Fig. 7. Schematic view of the forward extrusion process. Extrusion and ejection steps.

Finite element analyses of the forward extrusion is performed according to the numerical strategy presented in fig. 6. The material data required by the damage model are identified from tensile and shear tests; data required by the lubrication model are identified by the UST the coefficient of friction, and by measurement for the roughness parameters [Fil22]. The comparison between the billets and the final geometries of the FEA are in good agreement (Fig. 8-d,e,f), with a correct prediction of the damaged area.

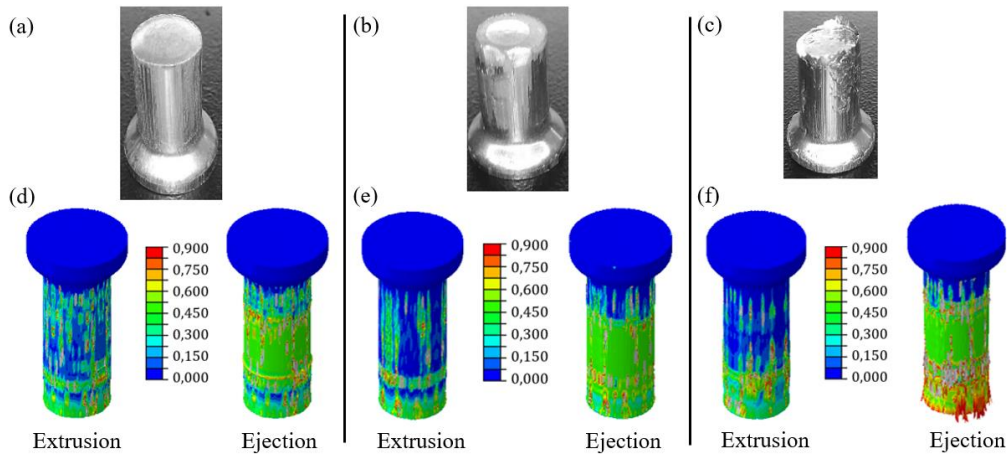


Fig. 8. (a) Experiments,  $R_a = 0.2 \mu\text{m}$ , with lubricant; (b) experiments,  $R_a = 0.2 \mu\text{m}$ , without lubricant; (c) experiments,  $R_a = 4 \mu\text{m}$ , without lubricant; (d) FEA,  $R_a = 0.2 \mu\text{m}$ , with lubricant; (e) FEA,  $R_a = 0.2 \mu\text{m}$ , without lubricant; (f) FEA,  $R_a = 4 \mu\text{m}$ , without lubricant;

We can then assume that FEA results are reliable and representative of the experiments. Figure 9 presents the number of damaged elements at the end of the extrusion step, at the end of the ejection step, and the total number of damaged element. This provides information on the severity of the galling occurring during the two forming steps of the process, information that is not accessible by experiments. First, it came that in the present case, the lubricant as almost no effect on preventing galling. This result may be due to the lubricant used for the test, which was a mineral oil without EP additive. Second, the number of elements affected by critical damage is three to four times larger during the ejection step than during the extrusion step. This highlights that galling occurs during extrusion, but that the surface defect is amplified during the ejection. Even though the materials and wear mechanisms are different, this result can be correlated with the observations of the WC dies for the extrusion of steel, where adhesive wear takes place along the calibration area (Fig. 4).

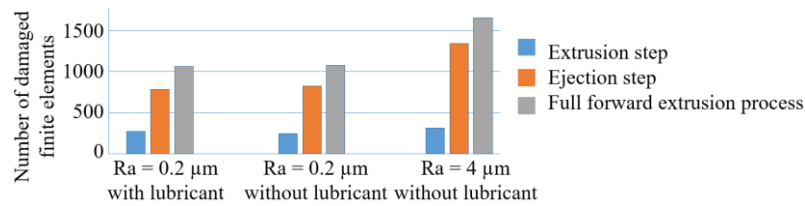


Fig. 9. Effect of process step, equivalent roughness and lubrication on the number of damaged elements.

## 6. Conclusion

A process centered approach has been involved to study different issues related to the cold forward extrusion process. Main results are:

- The choice of a lubricant requires tests performed at the actual temperature of the tool/part interface of the process. Test performed at room temperature may lead to erroneous conclusions.
- Wear modes of WC die evolves during the die life. Firstly occurring along the reduction area of the die, wear spreads towards the calibration area during the second half of die life.
- WC grains are deformed, fractured and subject to debonding. These surface defects lead to an increase of 100% of the coefficient of friction during its put into service and its end of life.
- Galling of aluminum during the extrusion process can be predicted by finite element analyses. FEA highlight that galling occurs mainly during the ejection step of the process.

## 7. Acknowledgement

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