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Temperature Effects on Organic Lubricants in Cold Forging of AA1050 Alloy

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Abstract
Lubricants have a key role in cold forging when pressures can reach extreme levels, since they contribute to reduce the high frictional forces occurring at the interface between the tools and billet. However, the adiabatic heating due to the high deformation rates may influence their performances with unpredictable consequences on the process stability. The objective of the research work is to investigate the friction behaviour of new environmental-friendly solid lubricants under process conditions with particular attention to the dies temperatures. The case study refers to the impact backward extrusion of AA1050 alloy cans. The newly developed testing set-up allows heating up the dies and the billet in order to reproduce controlled conditions of the tool temperature in the range 20-200°C. By matching the extrusion loads from the experiments carried out at different temperatures and the results of numerical simulations, the friction factors for each lubricant were determined.

Keywords: cold forging, lubrication, temperature, aluminum alloy AA1050

1 Introduction

One of the most relevant aspects of cold forging is represented by the high pressure at the interface between the tools and the workpiece, which can reach local values up to 2500 MPa with temperature peaks in the range of 300 - 400°C, while surface expansion can be as large as 3000% (Bay, 1994). In particular, galling is still a relevant issue in aluminium cold forging (Groche, Muller, Stahlmann, & Zang, 2013) since the loads at the interface between the tools and the workpiece are very demanding for the tribological system. As consequence, friction is a key aspect for the competitiveness of the process and it is essential that lubricants may withstand with high stability the interface conditions encountered in the different forging stages (Altan, Schrader, & Shirgaokar, 2007). Traditional oil-based lubricants, which are still the most commonly used in cold forging, present the twofold advantage of good lubrication and cooling properties, but they often need costly final cleaning operations that are critical for the economic competitiveness of the processes and the environmentally-related aspects. With regard to the latter and to the increased attention to labourers' health, worldwide legislations have become more and more restrictive concerning the use of hazardous lubricants in industrial applications (Bay, et al.,

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2010). The tribological systems often consist of a conversion coating as lubricant carrier and a lubricant (Hu & Dean, 2000) and the most common system for the lubrication carrier is a zinc-phosphate coating (Bay, 1994), which has a negative environmental impact (Takeuchi, Ikesue, & Kashimura, 1999) (Dubar, Bricout, Wierre, & Meignan, 1998). To overcome such limits and restrictions, suppliers have recently spent large efforts in the development of new lubrication systems with the target of eliminating hazardous chemicals (i.e. chlorinated or phosphates additives with metal sludge), reducing lubricant waste (with attention to reuse) as well as prolonging tool and lubricant life. However, the development of new lubrication systems brings up the issue about the methodologies and the techniques to evaluate their performances in industrial applications in terms of surface expansion, temperature of billets and dies, contact pressure and sliding velocity (Ruan, Saiki, Marumo, & Imamura, 2005).

A review of the scientific literature shows that many researches have already been focused on approaches to evaluate the effects of process parameters and a number of tests for cold forging processes have been developed to date. The performances of environmentally-friendly lubricants for cold forging operations were evaluated using the double cup backward extrusion test and numerical inverse analyses by Gariety (Gariety, Ngaile, & Altan, 2007), but the Authors pointed out the need of new tribo-tests at elevated temperatures and different ram speeds to assess the lubricant behaviour. In order to reproduce more severe testing conditions, Bay (Bay, Wibom, & Nielsen, 1995) analysed the friction through a test that uses a backward can extrusion and subsequent rotation of the punch with respect to the workpiece and the die under constant load. Sawamura (Sawamura, Yogo, Kamiyama, & Iwata, 2014) evaluated the friction coefficients of lubricants by means a slow rotating backward extrusion, which enables to create high pressure, large surface area expansion and a long sliding distance. Wang (Wang, Lin, Huanga, & Yun, 2008) proposed a real-time measuring method to evaluate the friction coefficient based on two approaches for the ring compression test, measuring the inner radius in case of high friction values by means image processing techniques, and the expansion inner radius at the low friction condition by strain gage measurements. Unfortunately, the main limitation of such approach lies in the limited surface expansion that can be obtained by the tests, thus limiting its application to simple upsetting processes. More recently, Sagisaka (Sagisaka, Nakamura, Hayakawa, & Ishibashi, 2013) proposed a new friction test based on combined forward spline-backward can extrusion to investigate the possibility to replace the aluminium fluoride coating with environmentally friendly lubricants. The main feature of the novel test was the capability of reproducing the large surface expansion that is typical of many cold forging processes, but the influence of temperature was not investigated in deep. Several Authors (Bay & Hansen, 1985) observed that most of the tests are not able to accurately simulate the process conditions due to the small surface enlargement, the low pressure, or the lack of control of main test parameters, as the well known case of the critical control of the twist compression or pin on disk test. Furthermore, Zhang (Zhang, Feldera, & Bruschi, 2009) and Ngaile (Ngaile, Saiki, Ruan, & Marumo, 2007) observed that tests such as the spike test, the upsetting sliding test, the double cup and the ring compression test induce a very simple deformation path and relative small new surface expansion ratio, with pressures not comparable to those obtained in various industrial processes.

With the goal of enhancing the simulative capability of laboratory testing approaches and with particular attention to the temperature-related aspects, the paper presents the results of tribological investigations to assess the performances of new solid lubricants for cold forging, specifically developed to avoid the traditional phosphate deposition. To this aim, a thermal-conditioned testing set-up that reproduces in a laboratory environment an impact backward extrusion process has been developed. Thanks to its design, the novel apparatus allows the testing of different lubrication systems with accurate control of the temperatures in the range of the industrial processes. Finally, a numerical inverse analysis approach was used to determine the friction coefficients for the different lubricants as function of the process parameters.

2 Application case

The application case refers to the cold forging of aluminium cans used to manufacture pressurized dispensers for the cosmetics industry. The reference material is the aluminium alloy AA1050 with a purity level of 99.5%, which is commonly used in applications that require a high ductility, moderate strength and very high resistance to corrosion. Figure 1 shows the typical production line which counts several steps: (a) *lubricant deposition on aluminium disks*, through a tumbling barrel that rotates at 16 RPM for 20 minutes; (b) *impact backward extrusion*, to shape the cans; (c) *trimming* of the top side of the can, *washing and drying*; (d) *internal and external spray coating*, which is then cured in an oven in order to extend product life and preserve the integrity of the contents, (e) *painting and printing*, and (f) *edging and necking*. The most severe step of the forming sequence is represented by the impact backward extrusion, since it exhibits the highest levels of pressure, temperature and surface expansion, which are particularly severe for the lubrication and the dies service life.

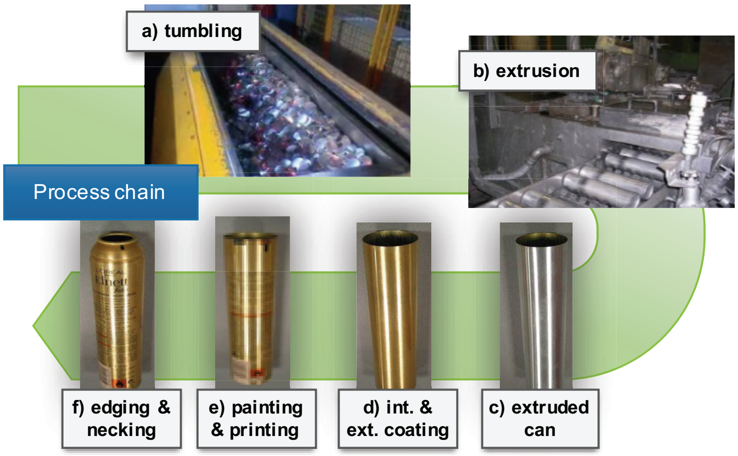


Figure 1: Main steps of process chain: (a) tumbling, (b) impact backward extrusion, (c) trim, wash, & dry extruded can (d) internal and external coating, (e) painting and printing, (f) edging and necking.

3 Materials

3.1 Test specimens and lubricants

The nominal chemical composition of the AA1050 aluminium alloy is reported in Table 1.

Cu	Mn	Fe	Si	Zn	Cr	Ni	Ti
0.05	0.05	0.4	0.24	0.07	0.05	0.05	0.05

Table 1: AA1050 nominal chemical composition (wt %)

The samples, in the form of blanked disks with a thickness of 4.2(±0.02) mm and a diameter of 30.8(±0.01) mm, are coated with different solid lubricants to be tested in cold forging conditions. Three lubricants are tested, namely: (i) the formulation *A* is based on soaps of heavy metals (Zinc), dispersant and anti-wear agents without any type of solvents, (ii) the formulation *B* that is based on alkali metal soaps combined together with different percentage of anti-wear and anti-corrosive agents, dispersants ethoxylates and esters fatty acid, and (iii) the formulation *C* is a metallic soap containing a high percentage of flammable solvent to ensure an optimal distribution of the film. Formulations *A* and *B*, have the advantage to be easily cleanable after deformation without the risk of flashing, as in case of the lubricant *C*. All the lubricants have wax as organic base component.

Energy Dispersive X-ray analyses (EDX) using a FEI QUANTA 450™ Scanning Electron Microscope (SEM) were carried out to investigate the surface chemical composition of the coatings using the low vacuum mode in order to not interfere with the organic content of lubricant. Figure 2 shows the comparison between the disks before and after the tumbling phase: the darker the colour of the area, the higher the quantity of the lubricant deposited on the disk surface, as proved by the spectra of the EDX analyses. The investigations confirm that the application of the lubricant by tumbling is not homogeneous on the disk surface, thus leading to large scattering of the lubrication performance.

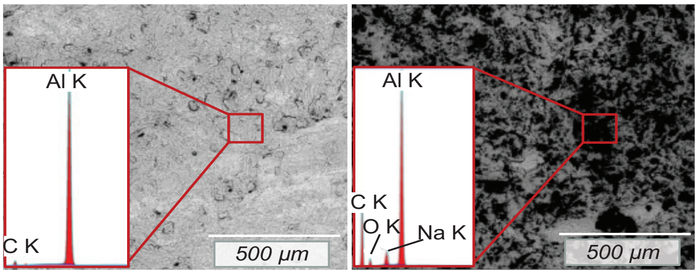


Figure 2: SEM image of the uncoated (left) and coated (right) disks and EDX spectra of the marked area.

3.2 Punches and dies

The steel grade used for the punch is the EN HS 6-5-2 alloyed steel, commercially available with the name of Böhler S600 (see the nominal chemical composition reported in Table 2). The steel was thermally treated, in order to obtain a surface hardness of 62(±1.5) HRC. The punches used in the experiments were machined to obtain a final surface roughness S_a of 1.735(±0.001) µm.

	C	Mn	Si	Cr	Mo	V	W
S600	0.9	-	-	4.1	5.0	1.8	6.2
W300	0.4	0.4	1.1	5	1.3	0.4	-

Table 2: Nominal chemical composition of the punches and dies materials.

In the case of the die, the steel grade is the EN X37CrMoV51KU, commercially available with the name of Böhler W300 (see the nominal chemical composition reported in Table 2). The die steel was thermally treated, to obtain a surface hardness of 54(±1.5) HRC. The final surface roughness S_a is equal to 0.563(±0.001) µm. Figure 3 shows the punch and die surface and metal disc non coated in the as-delivered conditions.

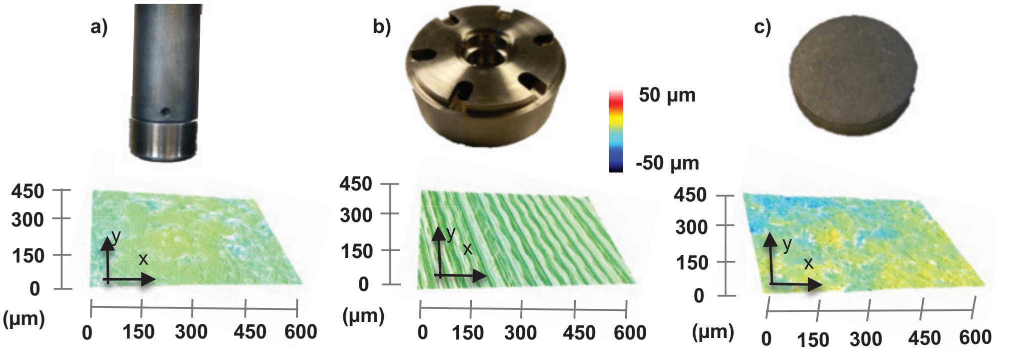


Figure 3: Surface topography of: a) the punch, b) the die and c) the aluminum non-coated disk in the as-delivered conditions.

4 Experiments

The impact backward extrusion test was conducted using a 2300 kN screw press in order to reproduce the same speed range of the industrial practice. Figure 4 shows the experimental equipment with the main details of the testing set-up.

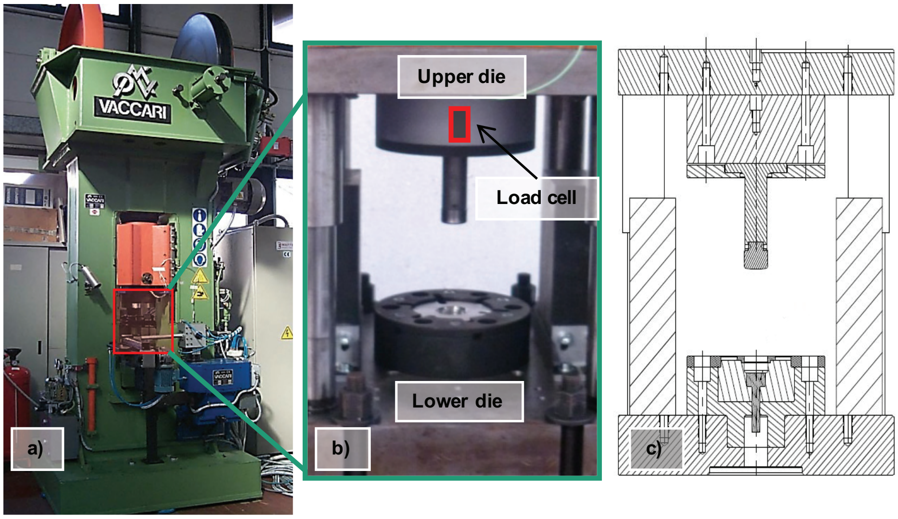


Figure 4: a) Laboratory pilot plant used in the experiments b) details of the set-up and c) CAD drawing.

The upper punch embeds a load cell for the measurement of the process force. The load cell basically consists of a steel element under the punch, whose elastic deformation is monitored by a piezoelectric strain measurement sensor that allows measuring the elastic deformation in the range ±1500 $\mu\varepsilon$. Calibration curves were obtained by applying a set of known loads and deriving the correspondent signal of the sensing element by means a converter that transformed from strain to Volt, see Figure 5.

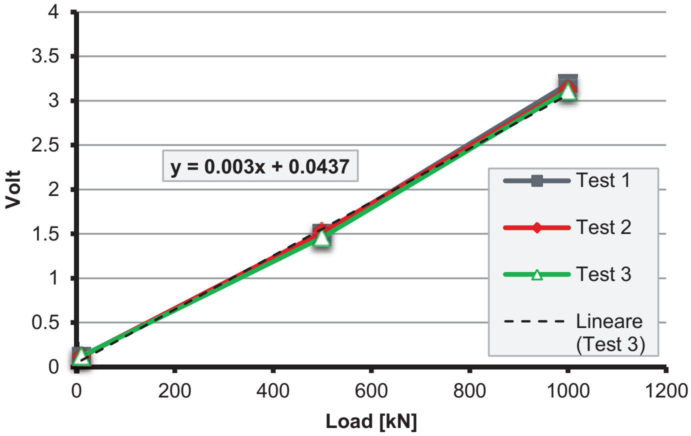


Figure 5: Calibration curves obtained by applying a set of known loads.

The lower die, namely the matrix, is thermally-conditioned thanks to six electric cartridges with a power of 200W each, which allow setting the initial die temperature up to 300°C. The temperature uniformity over the active surface of the die, equal to ±2°C, was optimized through FE simulations and experimentally verified by using an infrared thermo-camera. During the test, the lower die was heated to the target temperature and the thermal stabilization was awaited; subsequently, the disk, at room temperature, was inserted manually within the matrix. According to the industrial practice, the extrusion was initiated after a dwell time 2 seconds in each test; the extrusion process lasted 0.04 seconds. The thermal-mechanical cycle is illustrated schematically in Figure 6a, and Figure 6b shows the extruded can.

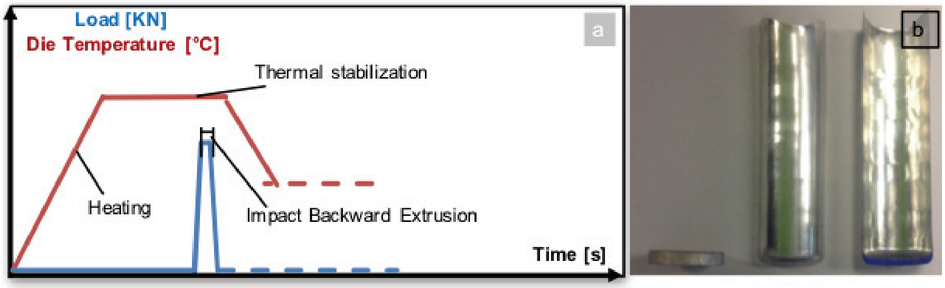


Figure 6: a) The thermal-mechanical cycle; b) metal disk can extruded and relative section.

According to the industrial practice, the ram speed was fixed at 225 (±3) mm/s for all the tests and the extruded part height was 80 (±1) mm. Table 3 shows the experimental plan, where the ranges of the investigated parameters, namely the billet temperature, the dies temperature, the ram speed and the type of lubricant, are reported. A minimum repeatability of 5 was assumed for all the tests.

Lubricant	Nominal Billet temp. ±2 [°C]	Die temp. ±2 [°C]	Ram speed ±3 [mm/s]
A-B-C	20	20 50 100 150 200	225

Table 3: Experimental plan of the impact backward extrusion test.

5 FE Model

The FE software FORGE 2011® was used to simulate the impact backward extrusion, with the Optimizer Tool embedded in the suite for the inverse analysis. By means of the algorithm, the user can submit the forming problem directly to the software application, by choosing the criteria to be optimized and the variables to be modified.

On this basis, the difference between the values of the extrusion forces recorded in the experimental tests and the ones obtained from the FE simulations, respectively, was selected as objective function to be minimized. The friction factor m according the Tresca model (1) was chosen as the parameter governing the convergence.

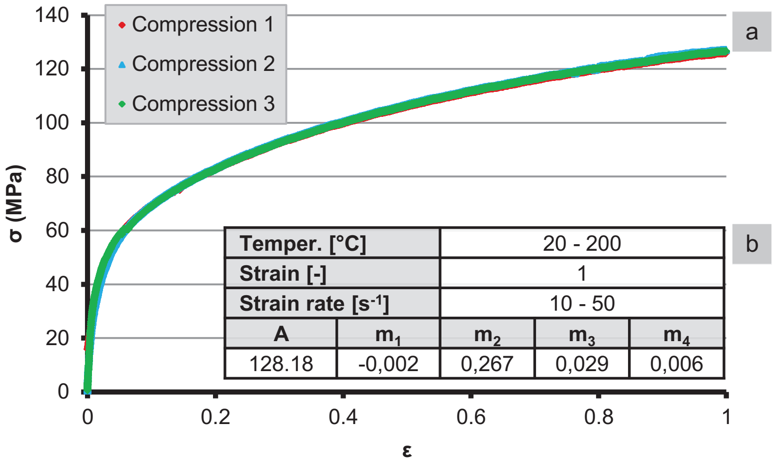
$$m = \frac{\tau_i}{k} \qquad 0 \leq m \leq 1 \tag{1}$$

where τ_i is the shear stress at the interface and k yield stress in pure shear.

The Hansel-Spittel (H-S) equation (2) was used as material model in the simulations, to take into account the effects of the strain rate and the temperature due to the adiabatic heating during the deformations:

$$\sigma = A \cdot e^{m_1 T} \cdot \varepsilon^{m_2} \cdot \dot{\varepsilon}^{m_3} e^{m_4/\varepsilon} \qquad (2)$$

where σ is the material trues stress, ε the material equivalent true strain, $\dot{\varepsilon}$ the equivalent material strain rate, T the temperature and A, m_1, m_2, m_3, m_4 the constitutive parameters. The latter were calibrated on the basis of flow stress curves experimentally obtained in the same range of temperatures and strain rates of the industrial process. Compression tests were carried out on cylindrical specimens having a diameter of 7(±0.02) mm and a height of 8(±0.02) mm, using a 10kN MTS hydraulic tester. The experimental curves are reported in Figure 7(a). Through a non linear regression analysis, the constitutive parameters of the H-S model were calculated to be implemented in the FE code and reported in Figure 7(b). The simulations were reproduced under the conditions of Table 3.



Temper. [°C]	20 - 200
Strain [-]	1
Strain rate [s^{-1}]	10 - 50

A	m_1	m_2	m_3	m_4
128.18	-0,002	0,267	0,029	0,006

Figure 7: (a) Example of the flow stress curves in the case of T=20°C and $\dot{\varepsilon}$=10s^{-1}, and (b) the constitutive parameters of the Hansel-Spittel model obtained by non linear regression analysis.

6 Results and discussion

Figure 8 shows a characteristic load vs. time curve experimentally recorded, where different phases can be identified during the forming operation. In phase *A*, the load rises up to the maximum level due to the impact of the punch with the disk and the impact speed of the screw press. Even if such behavior is not typical of the real process that is usually carried out on a mechanical press, the effect was considered acceptable since this phase was only an initial transient, during which little plastic deformation is obtained and the disk is simply enlarged to fill the lower die cavity. The phase *B* is non-stationary and corresponds to the beginning of the impact backward extrusion: the billet is further deformed and the backward material flow starts between the punch and the die. The material flow becomes stationary in the phase *C* that was taken as reference for the lubricant comparison. The last phase *D* represents the final part of the deformation when the ram rapidly stops.

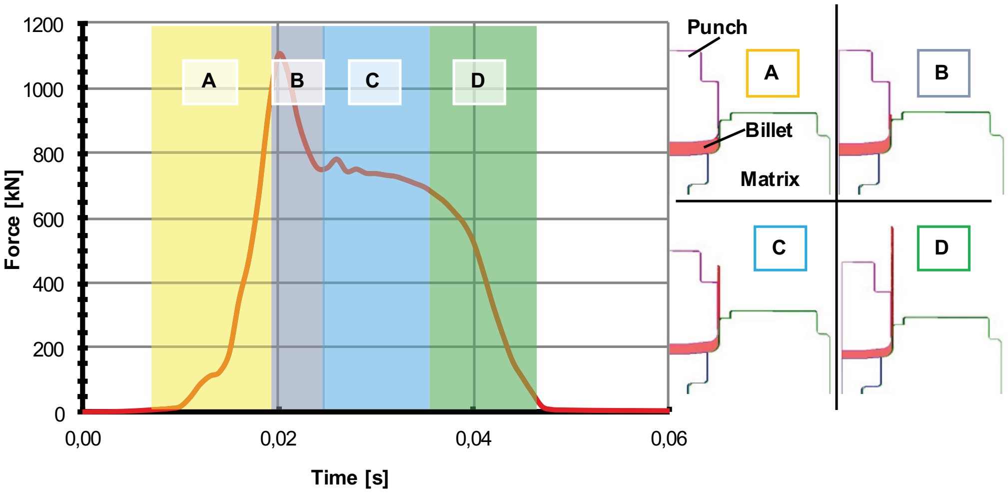


Figure 8: Load vs. time curve recorded during the experimental tests.

Figure 9 shows the experimental results in terms of extrusion loads vs. testing temperatures and the percentage of disk surface coated after the tumbling phase.

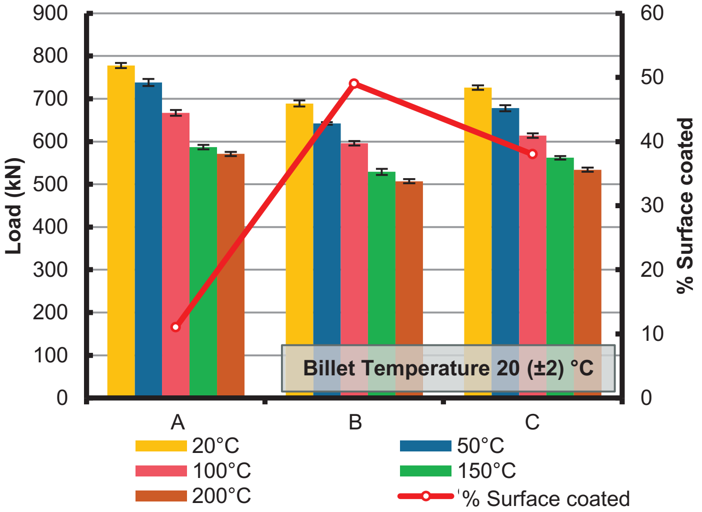


Figure 9: Extrusion load for different die temperatures and lubricants and percentage of disk coated surface after the tumbling phase.

A general overview of the results shows that the die temperature has a significant influence of the process load with all the tested lubricants and, in particular, the higher the die temperature, the lower the forging load. In addition to the influence of the temperature on the material flow stress that was estimated thanks the compression tests described in Section 5, the increase of the temperature at the interface between the die and the billet implies a sudden decrease of the wax viscosity, with a consequent better performance of all the lubricants. In such way, the lower viscosity determines a fall of the shear strength of the organic components of the lubricants and helps the activation of intra-film lubrication.

The comparison of the impact backward extrusion loads show that the formulation *B* has the best performance, with the loads ranging from 690(±7) kN and 510(±5) kN, respectively for the dies temperature at 20°C and 200°C. The formulation *A* shows the worst performance with loads that are about 11% higher than the ones measured with the formulation *B*. For all the tested lubricants, a transition temperature can be identified in the range between 100°C and 150°C, with an average load decrease of 11%; a further increase of temperature from 150°C up to 200°C determines a decrease of the measured load only equal to 3%.

The forging loads appear strongly correlated to the amount of lubricant that is deposited on the disks with the tumbling at the beginning of the production line, since it does not allow a uniform deposition and the surfaces of the disks results partially uncoated. So, to evaluate the efficiency of the lubricants deposition on the disk surfaces, image analysis techniques were used. For each side of the coated disks, six images with a resolution of 1020x940 pixels are recorded using an optical microscope, three with a magnification of 50X and three at a magnification of 200X, and afterwards post-processed with a specific software, ImageJ, an open source software with a specific tool dedicated to the analysis of greyscale images capable to calculate the areas covered by the lubricants by pixels analysis. The values are reported in Figure 9, while Figure 10 reports an example of the greyscale analysis carried out for the three formulations.

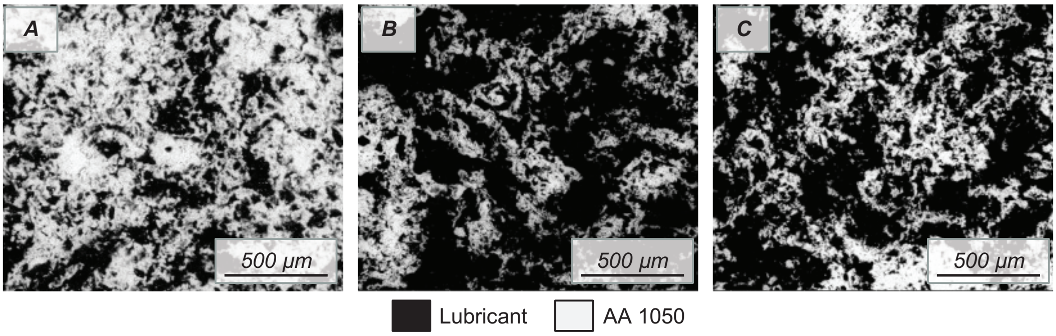


Figure 10: Example of the greyscale analysis carried out for the three formulations.

The results show that, despite the tumbling conditions are maintained constant in all the tests (1.2 g of lubricant/Kg of aluminum for all the formulations with a process time of 20 mins.), the efficiency of the deposition is strictly related to the chemical composition of the formulations, with a better adhesion in the case of the formulation *B* (percentage of coated surface equal to 49 (±0.5)%) and a worst adhesion for the formulation *A* (percentage coated surface equal to 11(±0.5)%). The formulation *C* presents a intermediate value of 38(±0.5)% of coated surface. The reasons of such behaviour are probably due to the higher amount of dispersants agents in the chemical composition of the lubricants *B* and *C*, that improve the separation of particles and prevent their settling.

Finally, the friction coefficients obtained with the different formulations were evaluated by using the FE numerical model presented in Section 5, estimating the softening effect that the temperature has on the material flow stress curves. Table 4 shows the friction factors, in the case of the lubricant *B*, calculated from the numerical simulations, by means of the inverse analysis procedure described at the Section 5.

Die temp. ±2 [°C]	Nominal Billet temp. ±2 [°C]	Load ±5 [kN]	Friction factor m
20	20	690	0.29
50		640	0.22
100		600	0.18
150		530	0.12
200		510	0.10

Table 4: Friction factors calculated by FE analyses in the case of lubricant "B".

An overview of the results shows that the initial die temperature has larger effects on the friction factor *m* than on the impact backward extrusion loads; this proving that higher interface temperatures contribute to improve the lubrication efficiency during the process, but have little influence on the material flow stress. Figure 11 shows the different trend of the loads and the friction factor *m* plotted vs. the dies temperature in the case of the formulation *B*, when the nominal initial billet temperature is 20°C as in the industrial process. While the impact backward extrusion loads are little influenced by temperature changes with a maximum variation of about 26%, the friction *factor m* shows a larger variation, with a decrease of about 66%, from an initial value of 0.29 down to a value of 0.1 at the highest die temperature. The same trend was found for the other formulations tested in the experiments.

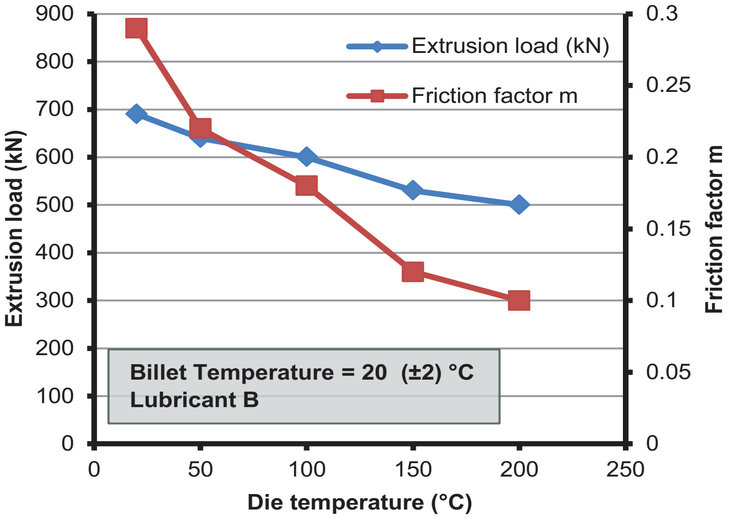


Figure 11: Influence of different die temperatures on the impact backward extrusion loads and the friction factor *m* in the case of lubricant "*B*".

7 Conclusions

The tribological properties of organic lubricants specifically developed to avoid the traditional phosphate deposition for aluminum alloys were investigated under cold forging conditions. The followed approach integrates physical and numerical simulation techniques and surface metrology methodologies, to investigate the lubricants performance as a function of the main process parameters. A novel testing apparatus was developed to investigate different lubrication systems with accurate control of the thermo-mechanical conditions at the interface between the billet and the dies in the temperature range from 20 up to 200°C. The experimental results show that:

- the amount of dispersants agents in the chemical composition of the lubricants may influence the adhesion of the lubricants during the application through tumbling, and, consequently, the loads measured during the impact backward extrusion.
- FE analyses allow evaluating that the temperature influence the performance of the lubricants and the friction factor *m* according to the Tresca model with a decrease up to 66% of the friction factor thanks to the when the temperature of the dies reaches the value of 200°C.

Next steps of the research work will focus on the investigation of the lubricants performances as function of the surface expansion, that could vary a lot during cold forging processes.

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