Investigating the relationship between the theoretical layer thickness of the graphite lubricant film and the Kudo’s friction number in the case of forged parts.

F Tancsics¹ and T Ibriksz¹

¹ Széchenyi István University AHJK - ATT, Győr, Hungary

E-mail: tancsics@sze.hu , ibriksz@sze.hu

Abstract. In case of numerical analysis of forged parts, it is important to specify the friction coefficient characterizing the lubrication conditions. In our paper we present a combined method of a known SU (Simple Upsetting) deformation with EDS (Energy Dispersive Spectroscopy), which shows the relationship between the Kudo’s friction number (this friction model is applicable for metalworking processes which produces high surface pressure) and the theoretical layer thickness of the graphite film covering the sink cavity. The tests were accomplished considering the solids content of non-synthetically produced lubricant concentrates diluted to varying degrees.

1. Graphite lubricants

One of the important technological step at hot impression die forging is removing the scale debrishes from cavity with compressed air and the uniform coverage of the cavity surfaces with layered crystalline solid lubricant that is mostly graphite. The operation has a significant impact on the life of the tools and the efficiency of the applied technology.

The characteristic feature of lubricant concentrate compositions of graphite content is that the so-called "solid lubricant" should be sprayed in a water-suspended state on the optimized temperature surface of cavity of the die [1-3] in technically acceptable dilution ratio. After vaporization of the carrier medium (water) the solid lubricant, which is a mixture of graphite and other different crystal structures, forms a continuous coating on the surfaces of the dies.

The most important constituent element of solid lubricant is the graphite, which is mostly derived from technologically processed mined flake graphite. According to mining forecasts, the demands of graphite flake amount in the world will increase to nearly fourfold in the next decade. The strong change is fueled by getting electric cars to the fore [4]. Taking this tendency into consideration, it is easy to recognize the importance of lubricants containing synthetic graphite, whose production costs are currently higher.

The goal of our work was to determine attributes for the qualification of mined flake graphite and synthetically produced graphite lubricants by linking the mined graphite content and average graphite particle size of lubricant to Kudo’s friction number.

2. Analysis of test methods, suitable model

During deformation of the work piece the displacement of the work piece contour points, which are contacted to the tool surface by the solid lubricant of lubricant, are essentially influenced by the crystal structure of the graphite. Graphite is the main component of the heterogeneous media between the work
piece and tool surfaces. This heterogeneous media, which contains large amount of graphite, is made up of mixed thin fine-grained scale- and oxide particles, debris chipped off the tool surface and solid lubricant of lubricant.

It is assumed that the relationship of the graphite content of the lubricant, which is sprayed onto the tool surface, the graphite particle size and the Kudo’s friction number, which affects the wear of the tools, can be detected in plant-operating conditions as well. The most important plant-operational markers (quality cost, specific lubricant usage, tool lifetime) can be determined based on this relationship, too. The amount of solid lubricant, which is sprayed onto the tool surface, can be calculated according to the following formula:

\[ m_F = c_{SZ} \cdot q_V \cdot \frac{t_f}{t_K} \int_{t_K}^{t_f} \eta \, dt \]  

(1)

whereabout:
- \( m_F \) the mass of the solid lubricant sprayed onto the tool surface [mg]
- \( c_{SZ} \) % by weight of solid lubricant in the suspension [mg/cm³]
- \( q_V \) volumetric flow rate of the sprayed suspension per time unit [cm³/sec]
- \( \eta \) the efficiency of spraying (lubricant loss at lubricant deposition and at vaporization) [-]
- \( t_K \) the time to reach initial temperature of the adhesion [sec]
- \( t_f \) the total duration of spraying [sec]

Function (1) is applicable both to those tool surfaces on which the temperature is higher than the adhesion temperature of the lubricant and the ones that are in the temperature range beneficial to the adhesion of the lubricant. Lubrication cannot be explained under the adhesion temperature.

Adequate tool temperature for lubricant adhesion and the adequate adhesion temperature range of the tool surface can vary depending on the lubricant concentrate composition. Adequate tool temperature from adhesion point of view are well approachable both by mathematical way [3] and experimental way. It is advisable to carry out the control experiment during lubrication tests on pre-heated plates at different temperatures. The control lubrication tests should be carried out on pre-heated plates whose temperatures represent the typical operating conditions. During the lubrication test, the applicable lubrication temperatures are determined by spraying lubricant on test pieces of different temperatures and the lubricant adhesion is checked. The coating should form a coherent matte layer on the surface of the correspondent test piece. At the appropriate range of temperature the desired coating is formed. Under this temperature flow strips and balling appear, above it blisters appear on the coated surface.

We applied this method to examine the adhesion range of a mined graphite type lubricant by determining the typical adhesion temperature of the lubricant. The result of this examination was between 150-200°C. This result means that all surface elements of the die cavity have to be within this temperature range.

The lubrication systems used on forging machines are extremely varied. Generally, they are characterized with their spray nozzle characteristics (classically full cone) and the spray pattern (mostly circular or ellipse). At setup of spraying pattern the type of nozzles and the technological characteristics (volume delivered per unit time, lubrication time, atomised drop size, etc.), the movement conditions, the position sets relative to the parting line of the die, the lubrication mode (direct or indirect, i.e. lubricant mist above the surfaces) and the surface roughness of the die should be considered. The lubricant spraying can be accomplished by hand and robots as well. The advantage of manual spraying is its technological elasticity. The substance loss about lubricant dispersion can be minimized more effectively, that is virtually negligible because the spraying pattern can be directly changed through the spray distance (drop size) and the valve opening size (through-flow cross section).

Changing the drop size the surface temperature of die cavity can be controlled or changed by the kinematics of drop vaporization [3]. Determining the thickness of the lubricant adhering to the die cavity
surface is more accurate if the surface of the tool is simpler, in other words, the number of the surface elements of the tool should be reduced as much as possible. Figure 1 shows a coating tape of an elongated ellipse-shaped spray pattern. The figure illustrates the theoretical distribution of the layer thickness and the dissipation band.

![Figure 1. Distribution of lubricant layer thickness. The arrows show the interval of dissipation loss.](image)

One of the most well-known tribometer method for layer thickness testing is the WHUST (Warm Hot Upsetting Sliding Test) test [9]. The method gives useful information on the optimum lubrication index (depending on the ratio of friction and normal forces) as well as on the appearance of scratches depending on the layer thickness of the lubricant applied on the surface.

In case of large surface pressures typical of forging, which induce equal or higher stresses than the yield stress of the tool steel, this method has not been proved yet. However, upsetting tests between parallel tool surfaces completely meet the forging conditions. During high-pressure deforming, the oxidation process becomes more intensive in the graphite crystals - due to the high pressure and temperature - which then accelerates above 600°C. During oxidation the layered crystal structure of graphite changes and its lubricity decreases [5]. Decrease in lubricity increases wear intensity.

The temperature range of the workpiece between 500-950°C (scale layer appearing) [6] and the temperature range of the tool surfaces above 450-500°C can be considered dangerous conditions for the intensity of tool cavity wear [1, 2, 8]. For the effect of high pressure on the surface partial sticking may occur as well. In this way the material flow will be realized inside the workpiece below the contacting surface [1, 7]. This should be avoided. The pressure distribution on the flat tool surface can be approximated by relation in Taylor's linearized form.

3. Operational experiments
The following conditions have been considered during the performing experiments. Conditions to simplify:
- the number of surface elements of the tool was reduced to the minimum (two planes)
- adjusting the spray pattern with manual spraying results in negligible loss of material (dissipation, vaporization), therefore the spray efficiency: 1
- solid lubricant deposition during the test time, i.e. the change in concentration of the suspended lubricant, negligible
- the lubricant layer thickness is steady on the tool surface and the thickness value of this meet the average of the Gauss density function
- during upsetting the friction number on the contact surfaces is characterized by a Kudo's friction number whose value is constant
- during upsetting the material flow stress is the same in all elemental volumes of the workpiece
Boundary conditions:
- surface temperature of the upsetting tools may only change within the adhesion temperature range characteristic of the lubricant
- when spraying lubricant onto the tool cavity surface, the technological settings are unchanged
- the deformation of the upset workpiece is symmetrical, only samples corresponding to this condition can be tested
- the lubricant application is considered satisfactory when the lubricant forms matte and continuous dry coating on the surfaces of tool cavity.

The solid lubricant content is typical of the lubricant type and it essentially determines the thickness of the graphite layer to adhere onto the tool cavity surface. Figure 2 shows the evolution of solid lubricant content (orange dots) of an Aquanet type lubricant concentrate (blue dots), expressed as a percentage by weight, depending on dilution. On the horizontal axis, the weight ratio of water (X) and lubricant concentrate can be read directly and on the vertical axis the solid lubricant content of the suspension is expressed as weight percent. At a 1:5 dilution, a yellow square marker shows the solid lubricant content tested in the laboratory. As a result of the test in laboratory, the solid lubricant content was 4.2%. This value is practically equivalent to theoretical 4.25%, so the theoretical data of Figure 2 are acceptable.

![Figure 2. Aquanet type lubricant solid lubricant content at various dilutions](image-url)

The upsetting tests were carried out in the forge-factory of Rába Axle Ltd on a maxima type presser of nominal force of 25 MN.

During the upsetting tests we recorded the following technological data: the dimension of lower tool flat surface is Ø200 mm, the dimension of upper tool flat surface is 320x300 mm, average surface roughness of tool surfaces Ra 1.6, the temperature of the tool surfaces measured in the axis line is between 150-160°C, Aquanet type lubricant usage in the following volume dilutions (lubricant concentrate / water) 1:4, 1:2, 1:1.

The temperature of the tool surfaces was measured by an INFRARED DT-882 optical pyrometer (50°C/+550°C). The lubricant was sprayed on the tool surfaces with manual spray gun in fine droplet (300-500 μm), with a flow rate of 0.43 liters per minute, with circular spreading pattern at 1 bar pressure.

The flow of volume was adjusted to the highest dilution (1:4) of lubricant, which was 50 cm³, to ensure the layer thickness changing in dilution proportion. The technology settings of the manual spray gun remained unchanged during the test. Additional technological data: number of steel test pieces are 15, geometry data of the test pieces before induction heating Ø50×100 mm (1.54 kg), measured material loss after a single induction heating 0.91%. The average temperature of the induction heated test pieces is 1177+/−20°C, adjusted upsetting height is 60 mm. The surface temperatures of the test pieces were measured by an INFRATHERM (IMPAC) IGA 15 plus optical pyrometer (250°C/+1800°C).
The Kudo's friction number is independent of the material flow stress, so it can be determined directly from deformation data of the cold dimensions of upset test pieces. The measurement accuracy of deformed test pieces in our case also required the material loss taken into account as well.

4. Analysis of the test results

To evaluate the upset test pieces a MathCAD algorithm based on UBET (Upper-Bound Elemental Technique) method was used [1, 10]. By this method, the axial and radial velocity functions are drawn from such a kinematic permissioned velocity field which is derived from a third degree polynomial. By means of the material flow factor (k), which can be expressed from the components of the velocity field, the deformation of the test piece can be characterized by parabolic approximation. Using this method, the complete upsetting process can be modeled numerically by taking law of the volume constancy into account. The parabolic approximation of deformation is scientifically accepted [1, 11].

The relation between the material flow factor (k) and the Kudo's friction number (m) is expressed by relation (2) [1, 10]:

\[ m = 1 - k. \]

Input data defined by measurement:
– geometry data of the test pieces after induction heating: Ø49.85x99.67 mm (1,526 kg),
– maximum diameter of upset test piece (barreled): \( d_{\text{max}} \) [mm]
– height of upset test piece: \( h \) [mm]

Output data defined by calculation:
– Kudo's friction number: m
– upset profile curve of workpiece (image of the velocity field might be plotted as well)

Using the MathCAD program, we plotted the profile curves for different dilution ratios and determined Kudo’s friction numbers (Table 1).

| parameters | dilution 1:4 | dilution 1:2 | dilution 1:1 |
|------------|--------------|--------------|--------------|
| \( d_{\text{max}} \) | 67.62 mm     | 67.13 mm     | 66.35 mm     |
| \( h \)   | 59.93 mm     | 60.07 mm     | 60.05 mm     |
| m          | 0.445        | 0.387        | 0.275        |

The Kudo's friction number which is shown in the column of 1:4 dilution is practically equal to the result of the same diluted Aquanet lubricant that we got before by SU (Simple Upsetting) and RCT (Ring Compression Test) test methods [1]. The results were verified by the finite element solver of Simufact forming for the largest upset diameter based on the specified friction numbers and input geometric data.

Important settings for analysis:
– analysis: General/2D axis/FE (Finite Element)/Cold
– applied mesher types: Advancing Front Quad (2D/1 mm finite element size) and Quad Tree (2D/1.6 mm finite element size) whereabout the mesh maximum refinement and coarsening values are equally 5
– mesh element type: Quads

The maximum diameters depending on the measured height after upsetting (59.3 mm), in case of \( m=0.445 \) friction number are as follows: AFQ mesh: 67.656 mm and QT mesh: 67.508 mm.

We have stated that the results can be influenced by the type of mesher and the minor deviation of the profile curve from the classical parabolic curve. Following the FEA (Finite Element Analysis) inspection, the theoretical layer thickness (referring to simplification conditions) of the solid lubricant sprayed on the tool flat surface was plotted as a function of the Kudo's friction number (Figure 3).
The layer thickness of solid lubricant sprayed on the tool surface was determined using Function (1) based on the atomization technology and geometry data of the tool. The lubricant required for full and proper covering of the tool surface was applied to the tool surface by hand spraying at a dilution ratio of 1:4 for 7 seconds. Later on, at each dilution ratio, the volume flown out during this time interval (50 cm$^3$) was applied. Thus, a different layer thickness per dilution came into being. It is noted here that constant 7 sec spraying time results in the same 15.70 μm layer thickness for all three dilutions (viscosity).

The EDS (Energy Dispersive Spectroscopy) assay was used to determine the graphite content of the solid substant. Determination of the graphite content was made on the basis of an appropriate quantity of sample in compliance with the statistical rules. During the examinations we also found such sampling sites, which has shown extremely different results. Deviations were defined as an anomaly of local concentration and we excluded them from the evaluation. The chosen method requires very accurate sample preparation and measurement, therefore the tests were performed on sample groups with 10KV and 20KV excitation voltages. Figure 4 shows the test result typical of the samples.

Based on Figure 4 we can state that besides the graphite the oxides are also present in the solid lubricant, mostly in the form of Na$_2$SiO$_3$/MgSiO$_3$ and solid graphite oxide (Na$_2$SiO$_3$/MgSiO$_3$ is providing uniform distribution of lubricant).
The pure graphite content of solid substant is approaching 86%. Based on the EDS results, after correcting the relationship shown in Figure 3 we obtained the correlation shown in Figure 5. The graph describes connection between the Kudo’s friction number and the theoretical layer thickness of graphite.

**Figure 5.** The change of the Kudo’s friction number as a function of the graphite layer thickness of the Aquanet type lubricant. Dashed line shows the result of the WHUST [9] test.

Figure 5 shows that the results of completely independent test methods show similarity to the attributes which characterized the functions. However, the friction coefficients considering the same layer thickness differ in approximately the same proportions, and are less than as the WHUST method. This deviation can be explained by difference between the test methods [1] [3] [9] and by the different average size of the graphite particles typical of lubricant types as well. So, in our case, we also need to examine the average size of the graphite flakes.

**Figure 6.** Graphite particle size changes depending on sampling location.

Figure 6 shows typical measurement results. Based on these results, the average particle size of the sample can be determined statistically by a good approximation. Here we note that only the well definable particle sizes were examined in 2D expansion.

It was found that the average typical particle size distribution is $D_{50}=6\,\mu\text{m}$, i.e. 6 microns is the median particle size distribution. The average size of flake fits in with the performance requirements of finely graphite lubricants applicable on finely machined tool surfaces (e.g. cavities of forging dies). Fine flakes create surface films by filling the micro-imperfections of the tool surface better (e.g. machining grooves). The average particle sizes of the WHUST test referred to above are bigger [9] than in our case but are still classified as fine particles in graphite based lubricants.

Comparing the observed differences of the particle size with the curves of Figure 5, further remarks can be taken:

- the difference in the dry lubrication state is caused by the different characteristics of test methods

the differences in the lubrication state are generated by the average particle size difference of graphite.

The latter remark is particularly important because of finer graphite particles, as the graphite layer thickness may be further reduced to a certain extent (depending on the tool surface quality, lubricant type) without having the thickness of the solid lubricant layer changed. This is important because we can avoid the splitting of the solid substant layer. This also means that it is possible to use lubricants of differing composition in more favourable dilution.

5. Summary, conclusions

In our work we were searching the relationship between Kudo's friction number and the layer thicknesses of flake graphite based lubricants. Our tests were carried out under operating conditions and with forging equipment. Correlation was found between the Kudo's friction number and the graphite layer thickness of lubricant referring to the lubricant based on content of mined flake graphite. The significance of this relationship is shown by the fact that we also found a link between the layer thickness and the average particle size distribution, which allows the thickness of the graphite layer sprayed onto the cavity surface to be reduced. This can assist in making more flexible lubrication technologies and making economic decisions about different type of lubricants.

We would say thank you for the following project: „Dynamics and direction of autonomous vehicles in the synergy of the requirements of automated traffic systems”. Code: EFOP-3.6.1-16-2016-00017.

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