Influence of heat transfer on the application of solid lubricant on hot dies

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This paper proposes a mechanism for the build-up of solid lubricant sprayed as a water suspension on a hot surface such as a casting or forging die. During this process, lubricant build-up depends on heat transfer in the die. A critical parameter named "sticking temperature" is proposed, which can be measured with simple equipment to characterize a lubrication system. Observations indicate that the amount of solid-lubricant deposited on the die is small relative to the total amount sprayed. A mathematical expression to calculate the amount of lubricant deposited on a die is presented, which is also useful to suggest strategies to improve efficiency of solid lubricant, minimize workplace contamination, avoid die-chilling in forging, and cold shuts in die-castings. This work is especially relevant for lubricant application during warm forging to minimize undesired effects during lubricant deposition on slugs.

1. INTRODUCTION

Solid lubricants are widely used in the forging and die-casting industries to protect the die from wear and soldering, to help release the formed component, and to provide the adequate boundary condition for the flow of material. Typically, they are applied as fine suspensions of solid particles (often graphite) in an aqueous carrier. This suspension is sprayed over the hot dies, where the liquid carrier evaporates, leaving behind a thin and uniform layer of solid lubricant. The amount of solid lubricant in this layer is critical to the process. In the case of hot metalworking, it plays a significant role in determining the friction coefficient. Figure 1 shows an actual example of measurements of friction coefficients between H13 die and mild steel billet with different amounts of solid lubricant[1, 2]. The friction coefficient in this case is defined as $m=\tau/\sigma f$, where τ is the frictional stress and σf is the flow stress of the billet. This is the definition typically used to characterize friction in forging[3]. It is clear from this figure that there is an optimal amount of graphite below which the friction increases, and above which the additional lubricant is not effective.

The effective application of solid lubricants is difficult when the forging or casting process require the dies to be very hot. In this case, little or no lubricant sticks to the surface. If lower initial die temperatures are used, or the spraying period is too long, die chilling can happen in hot metalworking, and cold shuts can happen in die casting. Die chilling is a phenomenon typically associated with dies that are too cold, thus cooling in excess the surface of the forging material, reducing its ability to flow, and leading for a high potential for defects. Other challenges of solid lubricant application are the dispersion of solid lubricant in the workplace, with the associated environmental and economic implications.

Most work on solid lubricants focuses on its tribological properties, and work on sprays typically focuses on their hydrodynamic and heat transfer properties. Relatively little attention has been devoted to the specific use of sprays to apply solid lubricants. Endres[4], and Liu *et al.*[5] performed a detailed analysis of the spray cooling of the die and the effect of different spray variables. Endres' work was aimed at minimizing thermal cracking in forging dies. Fraser and Jahedi[6] investigated sprayed lubricants to minimize galling and soldering on aluminum die-casting. Sheljaskow[7] presented an extensive analysis funded by the European Union aimed at developing environmentally friendly lubricants for warm forging.

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Iwama and Morimoto[8] performed an empirical study of lubricant adhesion during warm forging. This paper builds upon previous work on modeling of spray deposition[2, 9].

2. MECHANISM OF LUBRICANT APPLICATION

Industrial experience and controlled experiments show a consistent sequence of events during lubricant application on a hot die; this sequence can be divided into three stages, illustrated in Figure 2. During the first stage, the spray does not deposit any significant amount of solid lubricant or liquid on the die. In the second stage, solid lubricant adheres to the die surface without any traces of liquid. During the last stage, the spray wets the surface of the die, and the liquid running down washes out some of the solid lubricant deposited in the previous stage. Not all three stages are always present. It is observed that when the dies are too hot, only the first stage is present for normal spraying times. On the other hand, the third stage is seen only for excessive application times or initially cold dies. In industrial practice, the desire is to minimize the first stage, and to avoid the third stage altogether.

Knowing that the surface temperature of the die is lowered during spraying, the sequence of stages mentioned above suggests that the mechanism of lubricant application is related to die surface temperature, thus to heat transfer considerations. Two critical temperatures governing lubricant application are proposed: the “sticking temperature” T_k, and the “washing temperature” T_w.

The sticking temperature divides the first and second stages of application; above it, the spray acts just as a coolant on the surface of the die, the liquid carrier evaporates, and all the solid lubricant is dispersed in the air. The sticking temperature is likely dependent on the liquid carrier of the spray, the spray droplet size and velocity, and die surface conditions such as roughness and presence of oxides. The spray characteristics depend on the nozzle type and gas pressure used[4, 5].

The washing temperature is of the order of the boiling temperature of the carrier liquid, and divides the second and third stages. Below this temperature, part or all of the spray stays in liquid form and washes out the die surface. In between these two critical temperatures, the kinetics of evaporation of the spray are such that the solid lubricant is firmly attached to the surface of the die, with no traces of the liquid carrier.

This work focuses on the role of the sticking temperature, with the goal of investigating the proposed lubricant application mechanism, and to determine the sticking temperature for a particular system.

3. ANALYSIS

A representative way to test the mechanism proposed is by applying lubricant to a special die in which the heat transfer problem is one dimensional, and can be reproduced with simple equations. This way, the experimental setup is also simplified and of general validity, since it is not affected by the shape of a particular die.

Direct measurements of the surface temperature of the die indicate that the cooling of the surface follows the behavior of a surface convection boundary condition according to (1), which is illustrated in Figure 3.

$$T_s = T_0 - (T_0 - T_{amb})\left[1 - \exp(w)\,erfc\left(\sqrt{w}\right)\right] \qquad (1)$$

In (1), $w = h^2 \alpha t / k^2$, T_s is the temperature at the surface of the die, T_0 is the initial temperature of the die, which is assumed initially isothermal, T_{amb} is the ambient temperature, h is surface convection heat transfer coefficient, α is the thermal diffusivity of the die, t is time from the start of the spray, and k is the thermal conductivity of the die.

A thermal balance based on (1) indicates two important things. First, the rate of heat extraction from the die is not constant; second, the heat extracted from the die is less than expected if the entire liquid carrier was evaporated. These two facts suggest that only a fraction of the spray evaporates; this fraction will be called "evaporation efficiency" η_S. It will also be assumed that only this fraction of the spray contributes to the mass of solid lubricant adhered to the surface of the die; the rest of the spray will travel in liquid form somewhere else. This consideration implies that heat transfer and deposition of solid lubricant are coupled. The amount of solid lubricant deposited can then be calculated as

$$m_l = x_l \dot{m} \int_{t_k}^{t_t} \eta_s dt \tag{2}$$

Where m_l is the mass per unit area of solid lubricant deposited on the die surface, x_l is the weight fraction of solid lubricant in the liquid, $\dot{m}$ is the flow rate for the spray, t_k is the time it takes the surface of the die to reach the sticking temperature, and t_t is the total time the spray was on. Equation (2) considers that solid lubricant starts to accumulate after the die surface reaches the sticking temperature. This equation is valid for surface temperatures above the washing temperature. When the initial die temperature is the same or lower than the sticking temperature, t_k=0.

The evaporation efficiency of the spray can be obtained using heat transfer considerations. From measurements of surface temperature evolution, the heat extraction rate can be estimated as

$$q = h\left[T_s - T_{amb}\right] \tag{3}$$

Where q is the heat extraction rate, h is the surface convection coefficient, T_s is the surface temperature given by (1), and T_{amb} is the ambient temperature. This heat extraction rate can also be separated into two components, one due to evaporation of the liquid carrier, and another due to convective cooling from the gas phase:

$$q = \eta_s \dot{m}\left[r + c_p\left(T_b - T_{amb}\right)\right] + h_c\left[T_s - T_{amb}\right] \tag{4}$$

Where r is the latent heat of evaporation of the suspension, c_p is its specific heat, T_b its boiling temperature, and h_c is the effective surface heat transfer coefficient which considers convection from the gas and radiation. For the conditions of experiments presented here, convection is dominant over radiation, and a characteristic h_c of 300 W/m^{2}K is adopted. Combining (3) and (4), the following equation is obtained:

$$\eta_S = \frac{\left(h - h_c\right)\left[T_S - T_{amb}\right]}{\dot{m}\left[r + c_p\left(T_b - T_{amb}\right)\right]} \tag{5}$$

This equation shows that the evaporation efficiency parallels the evolution of the surface temperature, and decreases as the spray continues being applied. Replacing (1) into (5), and this last into (2), following expression is obtained:

$$m_l = \frac{x_l k^2\left(T_0 - T_{amb}\right)}{\alpha h\left[r + c_p\left(T_b - T_{amb}\right)\right]}\left(1 - \frac{h_c}{h}\right) I \tag{6}$$

where

$$I = \int_{w_k}^{w_t} \exp\left(-w\right) erfc\left(\sqrt{w}\right) dw, \tag{7}$$

and w_k corresponds to the time to reach sticking temperature on the surface, and w_t corresponds to the total spray application time. The integral of (7) depends only on w_k and w_t, and it is represented in Figure 4. Using Figure 3 and Figure 4 together with (6) it is possible to calculate the amount of lubricant adhered. The sticking temperature can be calculated from one or more experiments in which spray of known cooling characteristics is applied over a die at a known temperature and for a known time, and the amount of adhered lubricant is measured. This was the approach followed in this work. Equation (6), and Figures 3 and 4 enable this calculation using only basic algebraic operations.

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4. COMPARISON WITH EXPERIMENTS

Experiments were carried out to test the application mechanism proposed. A cylinder of H13 steel, 40 mm diameter, and 15 mm thickness was used as a die. The coefficient for surface convection was determined by measuring the evolution of the surface temperature during spraying. A K-type thermocouple was welded to the surface by capacitive discharge, as illustrated in Figure 5. The die was thick enough as to be considered semi-infinite for heat transfer purposes. The distance between the cylinder face and the nozzle was 160 mm. The atomizing nozzle used was an external mixing nozzle equivalent to a Lechler model #156.326.16.11. A protective screen was used to minimize cooling on the side of the dies, thus ensuring one-dimensional heat transfer.

Figure 6 presents the evolution of the surface temperature of the die during spraying. The measurement follows the behavior of a surface convection cooling process. At the beginning, a gradual decrease in temperature is observed where a sharp beginning of cooling would be expected. A relevant factor for this effect is the thermal inertia of the weld bead, which prevents it from measuring sharp changes. The rounding lasts about 0.12s, which is consistent with the radius of the weld bead (1mm). To account for this delay, the time variable in (1)was shifted 0.12s after the beginning of the rounded off part. Analysis of this curve using the thermal properties listed in Table 1 yield a surface convection coefficient of 13262 W/m^2K.

For the experimental verification of the mechanism proposed, Acheson Deltaforge 658 graphite suspension was sprayed onto dies similar to the one described above. Three initial die temperatures were selected based on temperatures used in industrial practice: 350 ^oC, 380 ^oC, and 410 ^oC. For each die temperature several experiments were carried, spraying lubricant for 0.25 s. To avoid start and stop transients during the spraying, a shutter was used. The spray started slightly before the application time, but it was blocked by the shutter. Similarly, after the desired application time, the shutter would block the application of spray, and then the spray nozzle would be turned off. In all cases the final aspect of the solid lubricant layer was smooth, flat, and continuous.

The mass flow of spray was measured by collecting the sprayed suspension on a beaker of 40mm mouth diameter located 160 mm from the nozzle, during 20 seconds. The weight fraction of solid lubricant in the suspension was measured by evaporation, and the amount of graphite deposited was measured as the difference in weight of the die before and after lubricant application.

Figure 7 presents the experimental results of the deposition of graphite at the three selected temperatures. (6) was fitted to these experiments using t_k (time to reach sticking temperature) as the only degree of freedom. The other parameters are listed in Table 2. The sticking temperature T_k, for each experiment was calculated using (1) evaluated at t_k. The seven measurements performed determined an average sticking temperature of 263.7°C (minimum 258.6 °C, maximum 271.2 °C). (6) predicts the correct trend and magnitude in the amount of mass deposited at each temperature.

Lubricant application efficiency is defined as the amount of solid lubricant deposited on the die relative to that contained in the spray. Experimental results show that this efficiency is relatively low (10% to 40%), and decreases with higher initial die temperatures. One of the consequences of this low efficiency is that a significant amount of the solid lubricant sprayed is dispersed in the work environment.

5. DISCUSSION

The good agreement between the experiments performed and the mechanism proposed is encouraging. The value obtained for the sticking temperature (263.7°C) is also reasonable. While the concept of sticking temperature is expected to be universal, the particular value obtained in this work is valid only for the spraying conditions of this work, and it is expected to depend on lubricant suspension properties, spray nozzle characteristics, and die surface conditions. Further research is necessary to determine the effect these variables on sticking temperature. Because the goal of this work was to determine the feasibility of the deposition mechanism proposed, the same properties were used in all the experiments performed.

The lubricant suspension can affect the sticking temperature by using different carrier liquids, or by using additives that change the evaporation kinetics of the droplets or the adhesion characteristic of the solid lubricant particles. The type of nozzle and the spraying distance determine the impinging droplet size, velocity, ratio of liquid to gas. The sticking temperature is expected to increase with droplet size, because larger droplets can absorb more heat before they evaporate completely. Following a similar reasoning, faster droplet velocities should also raise the sticking temperature. The die surface roughness and presence of oxides are also expected to affect the kinetics of boiling and mechanism of adhesion of solid particles. All these variables are also likely to affect the final appearance of the solid lubricant layer; for example, longer spraying distances produce lubricant layers with a more porous appearance. High speed video would be useful to study in detail the kinetic of solid lubricant deposition, and perhaps to relate it to the appropriate stages of heat transfer through a boiling film.

In this work, heat flow in the die is assumed perpendicular to the surface and governed by surface convection. In contrast with the flow of heat, fluid flow in the spray cannot be considered perpendicular to the surface. The fact that a fraction of the spray stays in liquid form to be deposited away from the die indicates that there is transverse velocity component for the spray droplets. More work is necessary to obtain a general relationship between fluid flow in the spray and the fraction of spray evaporated. Such a relationship is necessary for the accurate calculation of solid lubricant deposited on dies of complex shapes.

The mechanism proposed here can be extended to moving nozzles too. In this case, a traveling nozzle projects a moving spot of spray over the die surface. The front part of the moving spot would perform the initial cooling of the die surface down to the sticking temperature, while solid lubricant will build-up under the rest of the spot, as illustrated in Figure 8. For a typical moving nozzle with a spot size of 0.1 m, speed of the order of 0.4 m/s and H13 die, the cooling of the die during spraying can be considered one-dimensional, perpendicular to the surface, similar to the experiments performed. For such a moving nozzle, the equivalent spraying time is the residence time of the spray, which in this example is 0.25 s. Thus, for similar spraying conditions, the moving nozzle considered would produce solid lubricant layers similar to the ones measured in this work. A traveling nozzle projecting a circular spot will deposit a strip of solid lubricant narrower than that spot; this is because the edges of a circular spot have a shorter residence time; also, heat removal is less intense at the edges of a spray spot.

6. PROCESS IMPROVEMENTS

Figure 7 shows that the overall efficiency of solid lubricant application is low, especially for hotter dies. This has the unintended consequence of dispersing solid lubricant in the work environment, and it is economically undesirable. The reason for such low deposition efficiency is that in the initial stage of spraying, before the die surface reaches the sticking temperature, the liquid suspension only serves as a coolant. A possible improvement to the process is to divide the spraying onto the die in two stages. The first stage consists of spraying only water or some other liquid that acts as a coolant but that is less expensive or more environmentally friendly than the solid lubricant suspension. The second stage would start at a temperature slightly higher than the sticking temperature, and consist of spraying the solid lubricant suspension. This could be accomplished in static lubricant applications by using two sets of nozzles or by switching the feeding liquid of each nozzle. In moving nozzle applications, this technique could be accomplished by having a water nozzle precede the lubricant nozzle as they move, as illustrated in Figure 9.

In forging dies, a well designed lubrication system might help prevent die-chilling. More intense cooling might alleviate die-chilling, because the sticking temperature is reached faster, and the cooling affects a shallower region of the die. The smaller amount of cold die metal might solve the excessive cooling of the billet surface, and would help accomplish a faster press cycle. A similar approach might be employed to avoid cold shuts in die-casting, and to enable spray lubricant application on the slug during warm forging. In this last case, possibly, a high boiling point carrier like oil would perform better than water with a minimum of slug chilling. Conversely, if less intense cooling is necessary to improve die life, the mechanism presented here is useful to determine the least intense cooling that still provides acceptable lubricant adhesion.

The sticking temperature and the washing temperature define a window during which solid lubricant can be applied on the die surface; for a given spray, there is a maximum amount of graphite that can be deposited, as illustrated in Figure (2). If this amount needs to be increased, there are two main alternatives. First, the cooling intensity can be decreased by reducing the amount of liquid sprayed, which in turn decreases the heat transfer coefficient h. An inspection of (6) shows that between T_k and T_w, all variables are constant with the exception of h, which is approximately inversely proportional to the amount of solid lubricant deposited. Paradoxically, having a higher flow of liquid in the spray would result in a lower amount of solid lubricant deposited. This effect is consistent with the higher amount of heat absorbed by the die in the longer cooling time until reaching the washing temperature. If a spray containing less liquid causes die-chilling problems, a second alternative is to increase the amount of solid lubricant in the liquid carrier.

7. CONCLUSIONS

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Two die surface temperatures determine the window of applicability of solid lubricant. Above the higher temperature ("Sticking Temperature" T_k) the solid lubricant does not adhere and build-up on the die surface. Below the lower temperature ("Washing Temperature" T_w) the liquid suspension does not completely evaporate and runs in liquid phase over the surface of the die. For the experimental conditions of this work, a sticking temperature of 263.7 ^{o}C was determined, and a washing temperature of the order of 100 ^{o}C was observed.

In between the sticking temperature and the washing temperature, the amount of solid lubricant adhering to the die surface increases with spraying time, and it is governed by heat transfer in the die. For a continuous, uniform spray, the amount of solid lubricant adhered can be calculated using (6) with the help of Figure 3 and Figure 4.

The mechanism proposed is also valid for moving-nozzle applications. For typical solid lubricant application parameters, the heat transfer mechanism in the die is close to one-dimensional perpendicular to the surface, thus, (6) can be used. In this case, the spray application time is the dwell time of the moving spray spot.

The amount of solid lubricant adhered to the die surface is typically small compared to the total amount of solid lubricant contained in the spray (10% to 40%), with the associated economic and environmental disadvantages.

Assuming that the sticking and washing temperatures stay the same, the following process improvements are suggested: 1) Precede the spray of lubricant suspension by a water spray. This will minimize the amount of solid lubricant wasted during the cooling of the die at temperatures above the sticking temperature. 2) Use sprays with stronger mass flow to improve die-chilling problems. 3) Reduce the liquid flow of the sprays to deposit a higher maximum amount of solid lubricant between the sticking and the washing temperature.

Water-based solid lubricants and spray nozzles can be evaluated based on their effect on sticking temperature. A standardized testing procedure would be of help to set a baseline. Once the sticking temperature and the spray cooling properties are determined, computer models can be used to predict and optimize the amount of lubricant deposited in each part of dies of arbitrary shape. The concepts presented here can also be applied to robotic spraying arms. Given the critical relevance of the die surface temperature, sensors that measure it could be used to close the loop in advanced robotic implementations.

8. ACKNOWLEDGEMENTS

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Table 1: Parameters for measurement of surface heat transfer coefficient

T_{amb}	20 °C
T_0	450 °C
α	5.88×10^{-6} m^2/s
k	28.5 W/m

Table 2: Parameters used to calculate sticking temperature

T_{amb}	20 °C
h	13262 W/m^{2}K
h_c	300 W/m^{2}K
α	5.88x10^{-6} m^2/s
k	28.5 W/m
x_l	0.0507
$\dot{m}$	2.112 kg/m^{2}s
t_t	0.25 s
r	2.26x10^6 J/kg
c_P	4.18x10^3 J/kg K
T_b	100 °C

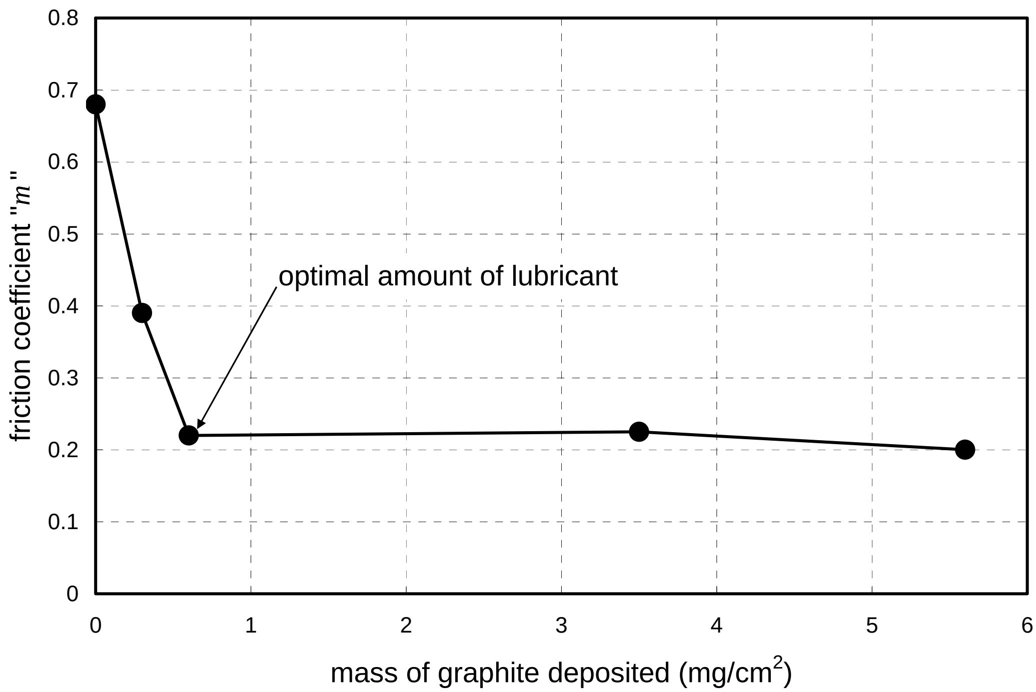

Figure 1: Dependence of friction coefficient with amount of graphite deposited[1]

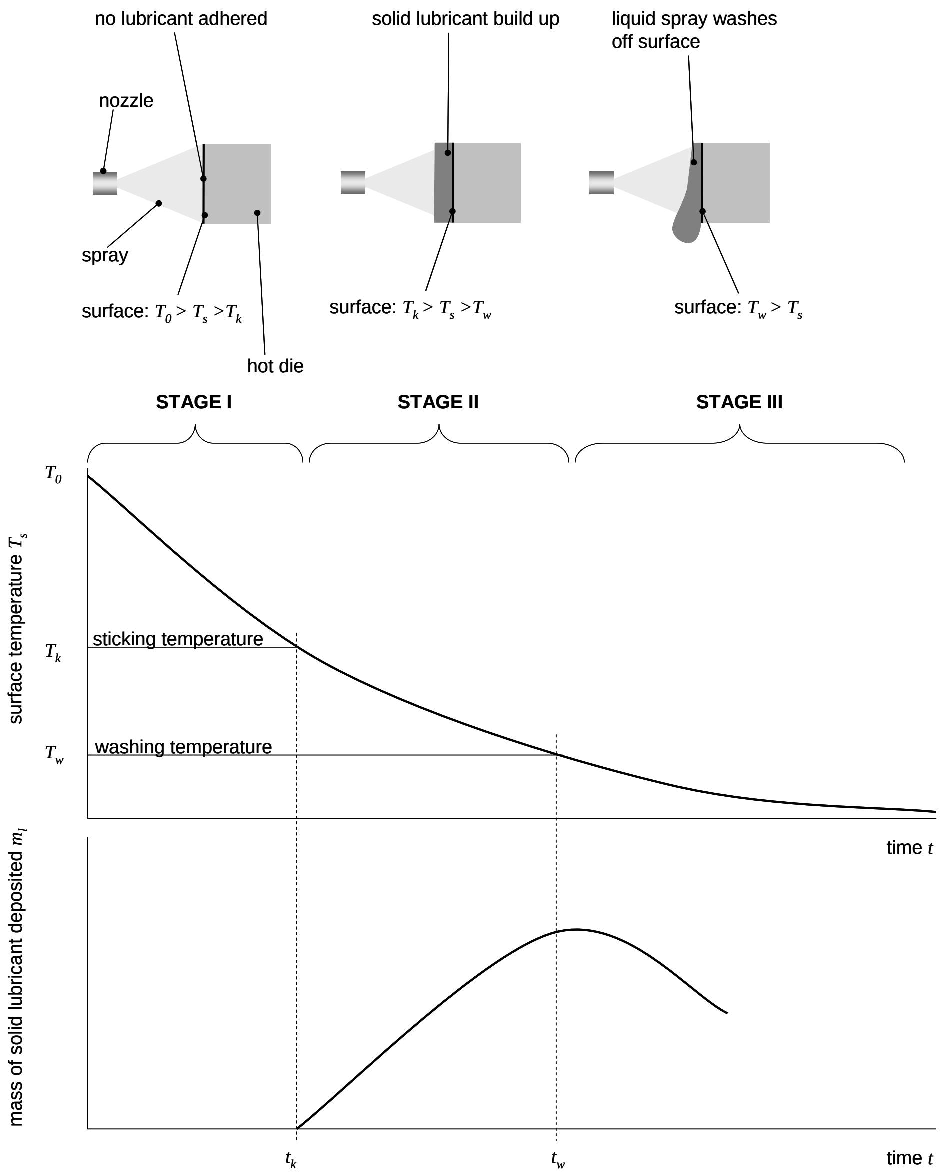

Figure 2: Stages in the application of solid lubricants on hot dies

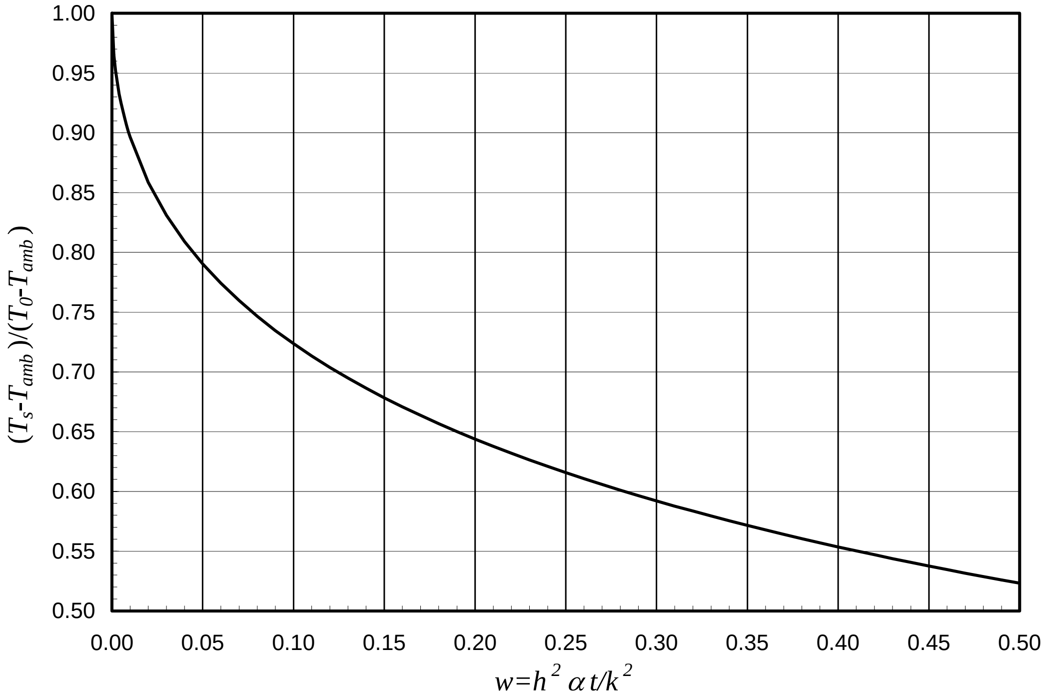

Figure 3: General evolution of surface temperature during spraying

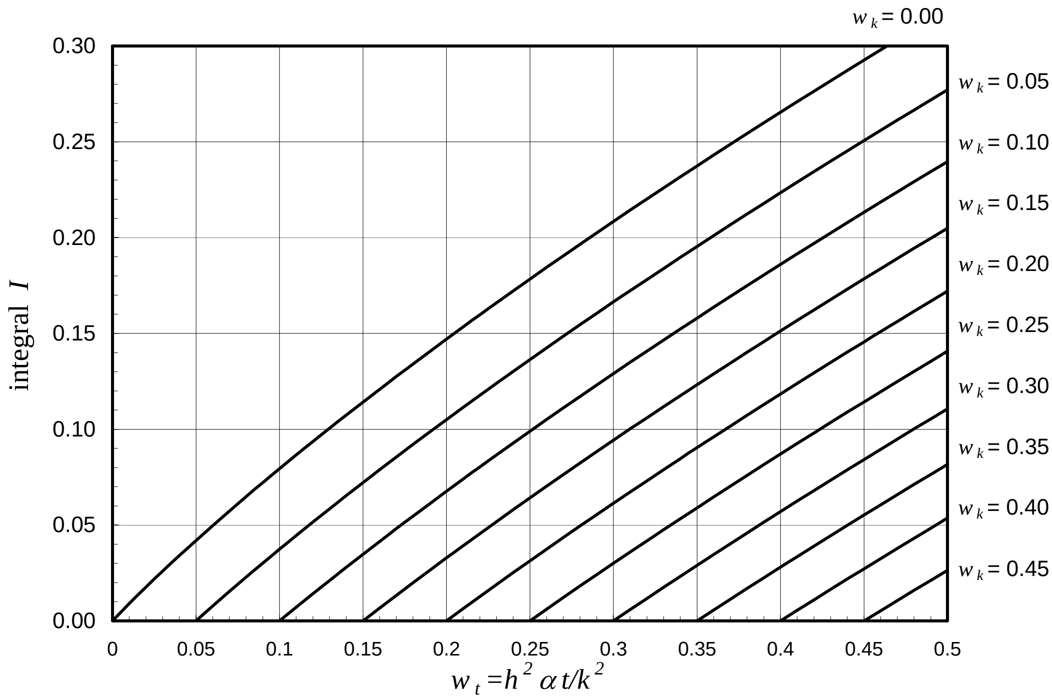

Figure 4: Graphic representation of $I(w_k, w_t)$

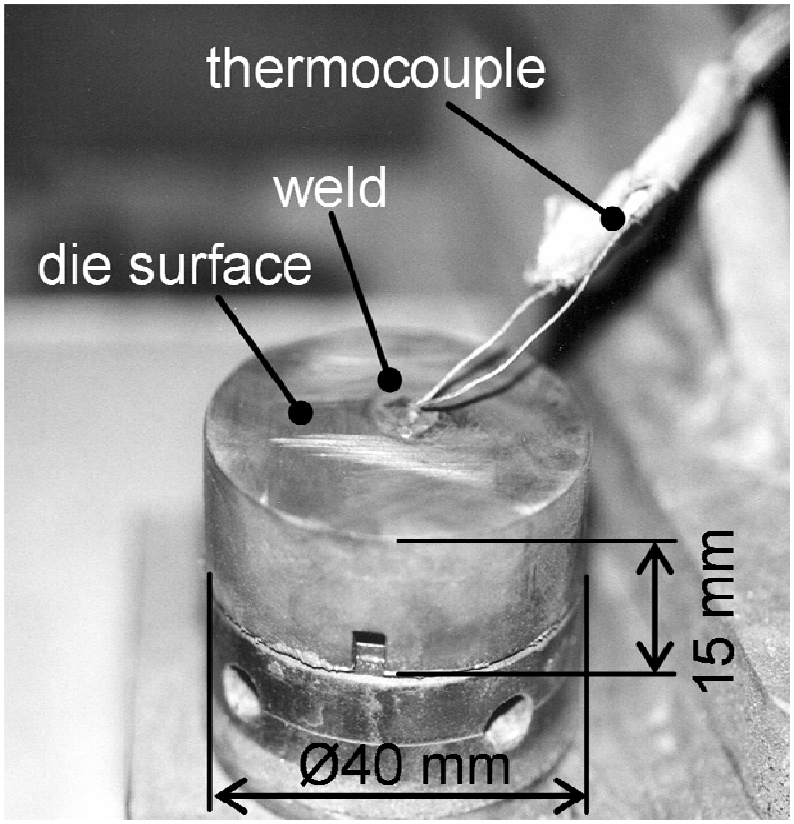

Figure 5: Setup for measurement of surface heat convection coefficient

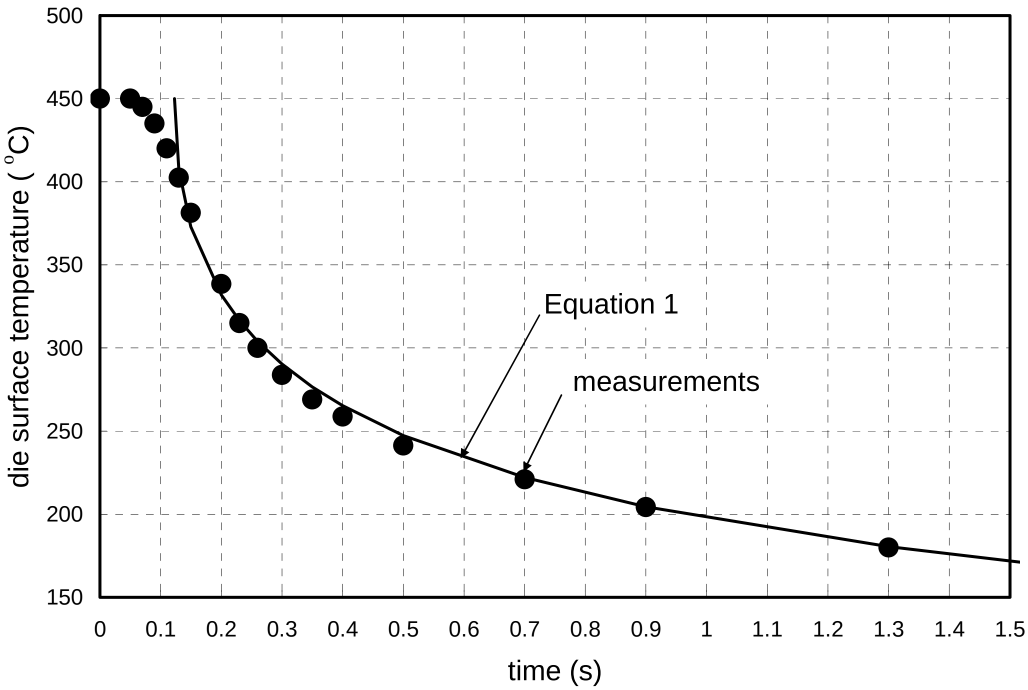

Figure 6: Surface cooling during lubricant application

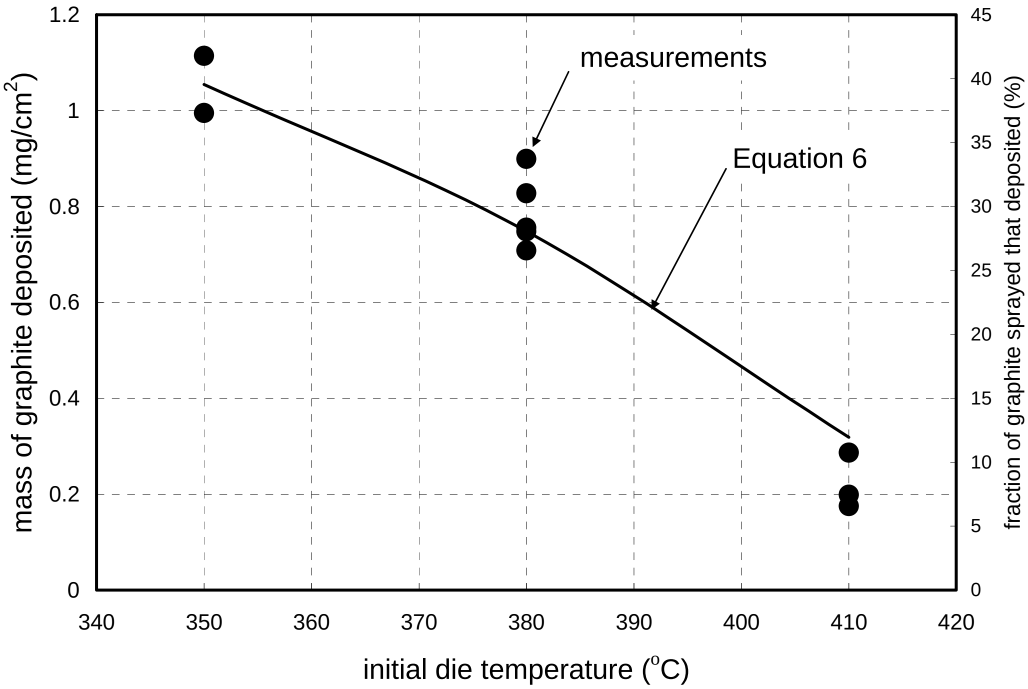

Figure 7: Predicted and measured amount of graphite deposited

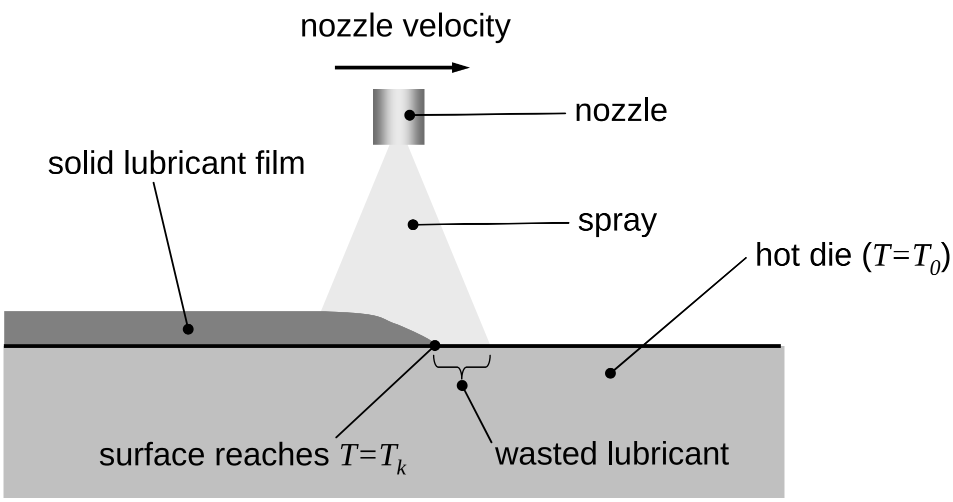

Figure 8: Lubricant application using a moving nozzle

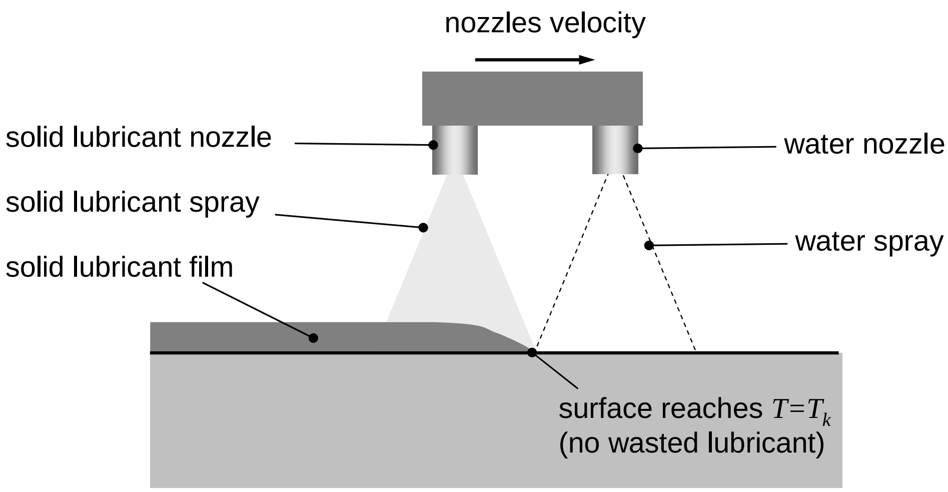

Figure 9: Lubricant application using a moving nozzle preceded by a water nozzle