Multiparametric study of Leidenfrost point and wettability of lubricants on high-pressure die-casting dies

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Abstract

This work is aimed at improving the lubricant film formation on the die surfaces in high-pressure die-casting (HPDC) pursuing enhancing cooling, temperature homogenization and casting release. An original test procedure was employed to study the Leidenfrost point (LFP) and the contact angle (CA) of various lubricants on die steel grades in the temperature range from 20 to 320 °C. The effects of various parameters such as steel grade, surface roughness, ageing, temperature, droplet size, water hardness and lubricant concentration on LFP and CA were isolated and analysed. It was found that the LFP remarkably increased for aged die surface with fine grains and relatively high roughness. The CA was affected mainly by the type of the lubricant. These findings lay the ground for optimal selection of the HPDC lubrication depending on the specific operating conditions.

Keywords

High-pressure die-casting; lubrication; Leidenfrost point; contact angle.

Highlights

- The contact angle (CA) depended mainly on the lubricant type and the die steel grade and varied with temperature
- The Leidenfrost point (LFP) was the highest for rough and aged H13 steel grade
- The Leidenfrost point was the highest for synthetic lubricant diluted in hard water at 3% and pulverized with a large nozzle
- Practical guidelines for effective multiparametric optimization of the CA and the LFP was developed

1. Introduction

High-pressure die-casting is a single step process producing accurate, thin-walled and very detailed light alloy parts at high productivity. Typically, molten light metal alloy (Al-, Zn-, Mg-based, etc.) is injected at high pressure into a steel die where it is solidified. After complete solidification, the die is opened and the die casting is ejected mechanically [1].

Quality remains an important issue for HPDC, which parameters must be optimized to completely exploit its technological potential [2]. Usually during the casting cycle the temperature on the die surface can vary between 80 °C and 500 °C [4]. Various researchers argued that sharp changes of the die surface temperature and its uneven distribution can be the reason of thermal cracking, soldering and thermal distortions of the die as well as lamination, shrinkage, cold laps and other defects of the casting [2-5]. Controlling the die surfaces temperature during the lubricant spraying within a narrower band around 200 °C [6] would be beneficial for increasing the useful die life and the surface quality of the casting. This also will contribute to reduce scrap, manufacturing cost and energy consumption [7]. For this purpose, lubricant is usually sprayed onto the inner contour of the die cavities at the beginning of each cycle pursuing to improve the temperature uniformity, create a film that facilitates the filling and the extraction of cast components (release agent) and, together with the surface oxide layer, prevent die soldering and adhesion [8].

Much effort has been focused on investigating the heat removal capability of lubricants sprayed onto a die casting dies [6, 9-11] as well as on the behaviour of drop splashing [12, 13]. The efficient heat transfer and wetting can be achieved at the temperatures below the Leidenfrost point (LFP) which serves as the temperature boundary between the transition and film boiling regimes [11, 14-16]. Various experimental investigations regarding the effects of droplet diameters and fluid properties on the Leidenfrost temperature of polished and nano/microstructured surfaces of aluminium, stainless steel, copper, nickel, silver and ceramics were carried out [10, 11, 17-21]. It was found that fluid properties, surface roughness of textured surface, and surface contamination were the most influential parameters for the LFP, whereas the surface roughness on the polished level and the contact angle (CA) have weak correlation with the LFP. The effect of additives and lubricant dilution on the LFP is not straightforward. Addition of surfactants to the lubricant can influence the dynamics of a bouncing droplet [18]. However, low dilution of lubricant provides lower heat transfer coefficient, than pure water [14]. The optimal formulation of the lubricant and its dilution must be experimentally found for each specific die casting conditions.

Increasing randomly distributed surface roughness is usually beneficial for both heat transfer and wetting on hydrophilic surfaces since it leads to biasing the LFP to higher temperature [11, 22] and decreasing the CA of hydrophilic surfaces, in accordance with Wenzel's model [23, 24]. It was also reported that the temperature of the LFP for superhydrophobic surfaces ($CA > 150^\circ$) could be significantly lower, than for hydrophilic ones ($CA < 90^\circ$) [25]. In contrast, developing regular microstructures on hydrophilic surface may notably reduce the LFP [26].

Among the parameters of the spray the following are the most relevant for controlling the heat flux removed: the dimensionless droplet Webber number (We), liquid Jacob number, volumetric flow rate, fluid composition, spray angle, droplet diameter, and subcooling [10, 27]. The Weber number being 12 times the ratio of the kinetic energy of a droplet to its surface energy [28], defines the breakup behaviour of liquid droplets impinging the hot surfaces. The following three general cases can be distinguished [25, 29]:

- $We < 30$ – a droplet bounces without disintegration;
- $30 < We < 80$ – a droplet disintegrates in several fragments after bouncing;
- $We > 80$ – a droplet breaks up into smaller droplets while splashing on the surface.

The dependence of the LFP on We is still under debate. Some authors argued that maximizing the We could be effective for shifting the LFP to higher temperature [25, 29, 30], whereas other reported little sensitivity of the LFP to the droplet velocity and We [19].

The analysis of the literature showed that the LFP and the CA being the indicators of the performance of spray lubrication depend non-linearly on the technological parameters. This considerably hinders optimization of spray lubrication since extrapolation of the available data, incomplete and mainly disembodied, is related with significant uncertainties.

In this study, the conditions at a liquid droplet/die material interface were experimentally simulated and the dependence of the LFP and the CA on various characteristics of the die surface (material type, roughness, temperature and ageing) and the liquid spray (lubricant type, dilution, water hardness and nozzle diameter) were isolated and analysed. The obtained results lay the ground for the methodology of the optimal selection of the HPDC lubrication depending on the specific operating conditions.

2. Materials and, experimental procedure

2.1 Materials

Five different concentrated HPDC lubricants in the form of 20-30 % emulsion were supplied by Motul-Baraldi and denoted hereafter as A, B, C, D and E, correspondingly. The lubricants contained oil blends, polysiloxanes, polymers and film forming additives. Emulsifiers and surfactants were added to stabilize the emulsion and to enhance the filming power on the die surface [31].

The B, D and E could be classified as semi-synthetic lubricants, since they contained mineral oil with viscosity index around 90. The A and C were synthetic lubricants with viscosity index approximately 180. The A and C had a very high releasing power and were intended for large weight die castings. The B was particularly indicated for thin-walled components of low weight, whereas the D and E were the general purpose HPDC lubricants.

The lubricants were prepared by dilution of the concentrates with water. The reference dilution rate was 1:50 (2%). Other dilution ratios between 1% and 20% were also screened.

Tap water (7.52 °dH German grade, 53.6 mg/l Ca^{+2} , <1 mg/l Mg^{2+}) and artificially prepared hard water (17.9 °dH, 96.8 mg/l Ca^{+2} , 18.7 mg/l Mg^{2+}) were used for dilution the concentrates.

Two common HPDC die steel grades – AISI H13 and H11 – were chosen for the study. The chemical compositions of the steel grades were determined using optical emission spectroscopy and are shown in Table 1. Both steel grades had very similar composition except V, which higher content in H13 leads to higher temperature resistance as well as higher resistance to wear and softening. Thermal conductivity and specific heat capacity: 28 W/(m K) and 460 J/(kg K), correspondingly, were also very similar for both steel grades as reported by the manufacturer. The steel samples were supplied quenched and tempered.

Table 1. The measured and nominal (according to AISI) chemical compositions (wt. %) of H13 and H11 steels

Steel grade		C	Si	Cr	Mo	V	Mn
H13	Nominal	0.39	1.00	5.10	1.35	0.90	0.40
	Measured	-*	0.91	4.85	1.33	0.96	0.35
H11	Nominal	0.38	1.00	5.10	1.35	0.40	0.40
	Measured	-*	0.99	4.90	1.20	0.31	0.40

* not measured by optical emission spectroscopy

2.2 Experimental set-up and procedure

A universal goniometer “SURFTENS” was used for the measurement of the LFP, the CA and the surface energy. This set-up based on the experimental device described by Nagai et al. [22] was modified to allow measuring both the LFP and the CA.

Fig. 1. The experimental set-up used for measuring the LFP and the CA.

The set-up (Fig. 1) consisted of a heater, a syringe with a connected nozzle and a dosing system. The sample was fixed to a hot plate of the heater, which temperature was controlled using a K-type thermocouple. The image of the droplet was acquired sideward using a digital camera. Two nozzles with the diameters of 0.5 and 0.9 mm were used.

For measuring the LFP the sample temperature was scanned in the range from 320 °C down to 80 °C in 20 °C steps. At each fixed temperature a drop of the selected lubricant was let fall onto a fresh surface of the sample, while the boiling regime was analysed using the camera. Then, a repeated experiment was done in a narrow temperature range with finer temperature steps. The lowest temperature in the studied range at which film boiling was observed was accepted as the Leidenfrost point. The uncertainty of the LFP was approximately ± 0.5 °C (for the temperature step of 1 °C).

The CA was determined using a sessile drop method at three temperatures: 25, 50 and 80°C. The CA was determined from fitting the droplet circumference at five points. Several images of the droplet were taken during 30 seconds after it was put on the surface. The mean value was determined averaging the CA obtained from various images of each droplet as well as between at least four repetitive tests.

The surface free energy of the die samples was determined using Wu's method [23] based on measuring the CA of distilled water (polar component) and diiodomethane (disperse component).

The surface tension of the lubricants at 2% dilution was measured using the Du Noüy ring method (Krüss K20 Easydyne).

The Rockwell C Hardness was measured according to UNE-EN ISO 6508-1:2015.

The surface roughness was measured by a stylus profilometer "Perthometer M2". The R_a values were determined following DIN EN ISO 4288 and 4287 standards.

3. Results and discussion

3.1 Materials characterization

Table 2 shows the measured surface tension of the five lubricants at 2 % dilution. Even at such high dilution the surface tension of all lubricants was significantly lower than for pure water, which surface tension is 72 mN/m.

Table 2. Mean values and standard errors ($\pm se$) of surface tension of the lubricants at 2% dilution

Lubricant	Surface tension (mN/m)
A	48.7 $\pm$ 0.60
B	53.2 $\pm$ 0.66

C	35.1±0.43
D	33.9±0.42
E	31.5±0.39

The microstructure of the steel grades is shown in Fig. 2. Both steel grades had tempered martensitic structure. For the H11 few precipitated carbides were found. The H13 steel had finer grain structure, than the H11 grade. This could be the reason for the higher hardness of H13: 47 ± 1 HRC against 40 ± 1 HRC of the H11 steel.

Fig. 2. Microstructures of the steel samples: a) H13 and b) H11.

The effect of surface finishing and in-service conditions on the surface roughness, R_a , of a real HPDC die was studied pursuing adequate simulation of surface microgeometry in the experiments. The following three types of surface finishing of a new die were chosen: (i) electrical discharge machining (EDM), (ii) milling using two different tools referred to as "a" and "b" hereinafter, and (iii) polishing. In addition, two zones of the die which were subjected to 15000 casting cycles were analysed: the one, where the metal flow was smooth, and another where the metal flow was turbulent. The results are summarized in Table 3.

Table 3. Roughness of the dies with surface finishing obtained using various methods as well as of the die subjected to 15000 casting cycles.

Surface finishing	R_a (μm)
EDM	2.02±0.04
EDM and milling (tool "a")	1.22±0.07
EDM and milling (tool "b")	0.80±0.12
EDM, milling and polishing	0.66±0.07
The die after 15000 casting cycles:	
zone of smooth flow	0.88±0.11
zone of turbulent flow	0.91±0.12

There are clear evidences that the die's roughness increased during the service life, and that this increase can be related with the severity of the operation conditions. On the basis of this analysis the R_a values of the samples for the simulation tests were selected between 0.02 and 1.8 μm .

In order to reproduce the real surface conditions of the die, the H11 and H13 samples were subjected to ageing for 5 hours at 600 °C in normal atmosphere. The analysis carried out after the ageing did not reveal any notable variation in microstructure and surface hardness, but in surface free energy

(Table 4). The polished samples of both steel grades had nearly the same surface free energy, whereas ageing led to different behaviour: for the H13 the surface free energy notably decreased, while for the H11 it slightly increased. The reason for this behaviour is not clear from this study and could be related with such factors as conceivable segregation of doping elements at the surface and microgeometry changing, among others.

Table 4. Surface free energy of polished and aged H13 and H11 steel samples

Steel grade	Surface finishing	Surface free energy (mJ/m ²)
H13	polished	39.9±0.49
	aged	23.3±0.29
H11	polished	40.7±0.50
	aged	46.3±0.57

3.2 The effect of temperature and steel grade

The behaviour of a bouncing droplet was screened for diluted lubricants and pure water at various surface temperatures in the wider temperature range from 320°C down to 80°C in 20°C steps. The We in this study varied between 9 and 64 depending on the surface tension of the liquid and the size of the droplet. The lower values corresponded to the lubricants A and B and the smaller droplet size. The findings of this preliminary experiment are the following:

- for both water and the lubricants the LFP was found in the range 140-160°C;
- above the LFP, the film boiling regime and the droplet behaviour were similar for all lubricants and water;
- below the LFP, the droplets of the lubricants and of water had different behaviour after impinging the surface. The droplets of the lubricants flattened and spread on the surface. The CA decreased until the droplet evaporated. Water droplets did not spread, but maintained the shape with the CA nearly constant in time. This difference could be attributed to the additives and surfactants which adhere to the die surface and pin the droplet. This, apparently, enhanced the contact angle hysteresis at the receding phase. In addition, migration of the lubricants on the surface contributed to the spread of the droplets. Considering variations of the droplets size and shape, and in order to reduce data scattering, all the measurements were done during 30 s after putting the droplet onto the surface.

Then, an accurate measurement of the LFP was carried out in the temperature range from 140 to 160 °C. Fig. 3 shows the LFP for the lubricants diluted in soft water on aged H13 and H11 steel grades.

Fig. 3. The LFP for the lubricants dissolved in soft water on aged H13 and H11 steel grades.

For both types of the substrate the LFP decreased in the following order: A>B>C>D>E. The H13 steel grade samples yielded slightly higher LFP values for all lubricants. This could be due to the differences in the surface microstructure such as finer grain structure of the H13, since thermal properties of both steel grades were very similar. The variation in the LFP between the lubricants should be attributed to the compositional differences.

The dependence of the CA on surface temperature is shown in Fig. 4. At 20 °C the mean CAs of the lubricants were in the range 44-67 and 38-47 degree for the H13 and H11 substrates, correspondingly. When temperature increased from 20 to 50 °C the CAs of the lubricants showed different behaviour, although with certain tendency to decrease. When the temperature further increased to 80 °C the CAs of all lubricants significantly decreased, while the E reached the minimal value of the CA among the lubricants. The higher CAs found for the H13 agreed with its lower surface free energy. The decrease in the CA with increasing temperature has been tentatively ascribed to partial water evaporation and the contact angle hysteresis.

Fig. 4. The CA at 20, 50 and 80 °C on (a) H13 and (b) H11 steel samples.

Fig. 5 shows the LFP of the five lubricants plotted against the corresponding CAs measured at various temperatures. For the H13 steel grade (Fig. 5 a) statistically significant linear trend could not be found at 20 and 50 °C due to considerable variability of the data: linear regression yielded high P values (0.43-0.58) and low R^2_{adj} (0.048-0.181). At 80 °C certain linear trend was observed (P value 0.08, R^2_{adj} 0.589). For the H11, the linear trend was significant (P value 0.077-0.010, R^2_{adj} 0.538 – 0.600) at all temperatures. The slope was positive in all cases and ranged between 0.15 and 0.38 °C/degree. Although the results should be taken with caution due to significant data scattering, they demonstrated that in many cases the LFP and the CA cannot be optimized individually through tuning the lubricant composition since improvement of the LFP (higher values) leads to worse wetting (higher CA).

Fig. 5. The correlation of the LFP with the CA for steel grades: (a) H13 and (b) H11.

Notable decrease of the CA was observed during the 30 s after the droplet placement (Fig. 6). After the initial transition period the rate of the CAs decrease stabilized. This rate was influenced by temperature. Apparently, the decrease of CA of the lubricants could be due to the two processes. On the one hand, migration of the lubricant along the surface could lead to the deformation of the initial shape of the droplet and it's flatter. On the other hand, water evaporation, which should be especially intensive at 80 °C, could produce receding of the pinned droplet. In order to evaluate the contributions of each of these two processes the measured data were fitted to the Tanner's model of the droplet spreading, which predicts that "the edge velocity is approximately proportional to the cube of the slope at the inflection" near the edge of the droplet [32]:

$$-\frac{1}{3}\ln(\beta(t)) \propto \ln(t), \quad (1)$$

where β is the slope, t is the time. The slope can be satisfactorily approximated by a tangent of the CA. The function $y = -\frac{1}{3}\ln(\beta(t))$ was calculated for the data shown in Figs. 6a-b and is plotted versus $\ln(t)$ in Figs. 6c-d, correspondingly. For all lubricants at 20° C, y could be perfectly fitted by linear functions in the whole range of t . High fitting quality is evidenced from the adjusted coefficient of determination, $R^2_{adj.}$, which ranged between 0.96 and 0.99. The slopes differed for synthetic and semi-synthetic lubricants: for the A and C, they were $(47.9 \pm 1.1) \times 10^{-3}$ and $(49.0 \pm 0.8) \times 10^{-3}$, correspondingly, whereas for the B, D and E, they were $(67.9 \pm 1.3) \times 10^{-3}$, $(61.2 \pm 1.3) \times 10^{-3}$, and $(64.9 \pm 2.5) \times 10^{-3}$, respectively. For water, fitting quality was not satisfactorily ($R^2_{adj.} < 0.6$) due to large dispersion of the data. At 80 °C y maintained the linear behaviour during the initial 15 s, although with considerably larger slopes (between 0.100 and 0.155), than at 20 °C, and then upturned. For water the plot significantly deviated from linear function.

Fig. 6. The dependence of the CAs of the lubricants and water on time on H13 steel grade at (a) 20 °C and (b) 80 °C. Plots (c) and (d) show fitting of the data from (a) and (b), correspondingly, by Tanner' model.

These findings suggest that at 20° C as well as during the initial period at 80° C the CA of all lubricants was controlled mainly by migration on the surface. This process is influenced by the oil viscosity: the slope of γ increases with decreasing viscosity [32]. This explains the increase of the slope of the plots in Fig. 6 with increasing temperature. There should be also some influence of the type of the base oil, since the slopes differed for the synthetic and semi-synthetic oils. After the initial period at 80 °C (non-linear part of the plots in Fig. 6d the CA of the lubricants had to be controlled mainly by evaporation as in the case of water droplets, which shrank with time rather than spread on the surface.

3.3 The influence of water hardness and dilution rate

The effect of the hardness of water used for preparation of the lubricant emulsions is shown in Fig. 7. The lubricants mixed with hard water tended to have slightly higher LFP (an increase by $0.8 \pm 0.22\%$), than the same lubricants mixed with soft water. This effect was the same for both steel grades. Increasing water hardness can enhance the LFP, while maintaining unchanged the CA.

Fig. 7. The correlation of the LFP values for the lubricants mixed with hard and soft water on H13 and H11 steel grades.

The effect of the dilution rate in the range 1-3 % was examined for some of the lubricants. Additionally, a higher dilution rate (up to 20 %) was investigated for the A/H13 lubricant/steel grade combination, which showed the highest LFP in the previous tests. The results are shown in Fig. 8. The behaviour of all lubricants was the same. The LFP steeply increased (on 4.6 to 7.0 %) when the dilution rate increased from 1 to 3 % and stabilized. The increase of the dilution rate above 5% led to small decrease in the LFP. These results are in agreement with literature [29]. Plausible explanation of the initial improvement in the LFP is based on the consideration that a droplet with higher lubricant concentration requires higher surface temperature to produce the critical vaporization rate and to overcome the weight of the droplet to lift out from the die surface [14]. Stabilization of the LFP at the lubricant concentration higher, than 3% can be related with the saturation of the droplet surface with the surfactants, so that additional amount of the lubricant has no effect on the surface tension.

Fig. 8. The effect of the dilution rate for various lubricants on the LFP.

3.4. The influence of surface roughness and ageing

The tests were performed with the A and B lubricants on various ground or polished steel samples. The LFP increased with the surface roughness for both lubricants and both steel grades. These findings are in agreement with the published results on the surfaces with irregular microgeometry [22]. The increase in surface roughness leads to decrease in the real contact that hinders heat transfer between a droplet and the surface. Therefore, higher temperature is needed to create sufficient vapour layer and establish the Leidenfrost effect.

Fig. 9. The influence of surface roughness on the LFP.

In the range of R_a from 0.022 to 1.84 μm no definite correlation of the CA with the surface roughness was found. This could be due to large scattering of the experimentally measured values of the CA that ranged between 57 and 67 degrees for the H13 and between 44 and 49 for the H11. The scattering was especially notable on the samples with higher roughness.

Fig. 10 shows the effect of ageing on the LFP for the A and B. For all studied combinations of the lubricants and steel grades ageing led to considerable increase of the LFP. This effect was more pronounced for the H13 steel. The effect of ageing can be interpreted in terms of lowering thermal conductivity of the surface oxide layer in comparison with the bare steel.

Fig. 10. The LFP for the A and B lubricants on as made and aged steel samples: (a) H13 and (b) H11.

3.5 The influence of the droplet size

Droplets of different size were obtained by varying the nozzle diameter. The LFP increased with the nozzle size for both steel grades as shown in Fig. 11. This finding is consistent with literature [25, 29, 30]. The larger droplets impinge the hot surface at higher We that provides better conditions for heat transfer. In addition, the larger droplets requires higher evaporation rate to produce Leidenfrost effect.

Fig. 11. The dependence of the LFP on the nozzle diameter.

As expected, the droplet size had no effect on the CA as shown in Table 5.

Table 5. Mean CA (deg.) and standard error ($\pm se$) for droplets obtained with different nozzle diameter on H13 and H11 steel surfaces.

Surface	0.5 mm	0.9 mm
H13	57 $\pm$ 3	59 $\pm$ 1
H11	59 $\pm$ 2	56 $\pm$ 1

Tuning the lubricant droplet size is critical for optimization of the HDPC process in terms of quality and efficiency. This is schematically shown in Fig. 12. At higher die temperature the lubricant must provide effective cooling that could be achieved by increasing the droplet size, which tend to shift the LFP to higher values. At low temperatures, typically below 180 °C smaller droplets size may avoid working below the temperature of critical heat flow, where the risk of porosity formation in castings due to vapour bubbles is high. A lower temperature leads to faster solidification of metal, enhancing its mechanical properties due to decreasing the grain size, and improving the overall casting quality. However, the energy efficiency is low due to the need of intensive cooling of the dies.

Fig. 12. Schematic drawing of temperature region and corresponding optimal droplet size.

3.6 Considerations for lubrication optimization

Simultaneous maximizing of the LFP and minimizing of the CA is the objective of the lubrication optimization pursuing to improve the heat exchange and capacity to create a film. These two characteristics are tightly and non-linearly linked, so the LFP and the CA cannot be isolated and optimized individually through tuning the lubricant composition. The present study has elucidated the dependencies of the LFP and CA on various technological parameters that lays the ground for development of practical guidelines of effective lubrication optimization. It is suggested to carry out the optimization in two steps (Fig. 13). At the first step, the CA can be minimized with respect to the possible combinations of the die material (steel grade) and the lubricant. This should be done in the temperature range corresponding to real service conditions since the CA is heavily influenced by temperature. At the second step, the LFP can be maximized through tuning the parameters which affect the CA only slightly. These parameters include the surface-related properties (surface roughness and surface oxidation state) and the lubricant-related ones (water hardness, dilution rate and the droplet size).

Fig. 13. Schematic diagram of the effective multiparametric optimization of the die lubrication.

For instance, in the ranges of parameters of this study the optimal configuration is the following: aged H13 steel grade lubricated with the A lubricant diluted at 3% using hard water and pulverized by a larger nozzle. In comparison with nonoptimal configuration, the LFP could be raised from 145 to 165°C, while maintaining low CA.

4. Conclusions

The dependence of the Leidenfrost point (LFP) and the contact angle (CA) on various characteristics of the die surface (material type, roughness, temperature and ageing) and the liquid spray (type of the lubricant, dilution, water hardness and the nozzle diameter) have been investigated. It was found that increasing of the LFP till 165 °C, that is beneficial for effective lubrication and heat exchange, can be achieved by optimization the lubricant-related and the surface-related parameters. The lowest values of the CA were found for the combination of H11 grade steel and semi-synthetic lubricant E. A positive correlation exists between the CA and the LFP at the temperature 80 °C, which makes not possible to minimize CA and maximize LFP at the same time by working with lubricant or steel selection.

A practical guideline for effective optimizing the die lubrication has been suggested. It implies a two-step approach: first, the CA is minimized though the selection of the lubricant and the steel grade at given temperature, and the second, the LFP is maximized by tuning the surface-related (roughness and oxidation condition) and the lubricant-related parameters (water hardness, dilution rate and droplet size).

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