



# 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.

## 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

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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 Weber 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 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 B, D and E were semi-synthetic lubricants with viscosity index around 90, whereas A and C were synthetic lubricants with viscosity index 180. Dynamic viscosity and viscosity index for the formulated base oils are shown in Table 1.

Kinematic viscosity of concentrated emulsions was measured following the ASTM D445 standard at room temperature (26 °C) and 40 °C. Coefficient of variation for all measurements was below 0.002 and the determinability was below 0.9%. The results are shown in Table 2. All the emulsions show quite similar viscosity, which values

**Table 1**  
Dynamic viscosity and viscosity index of the base oils used for the lubricants formulation.

Base oil	Viscosity at 40 °C (mPa s)	Viscosity Index
A	65	180
B	190	90
C	65	180
D	190	90
E	190	90

**Table 2**  
Kinematic viscosity of the concentrated emulsions obtained at two temperatures.

Concentrated emulsion	Viscosity (cSt)	
	26 °C	40 °C
A	2.62	1.95
B	2.15	1.61
C	2.32	1.61
D	2.31	1.74
E	2.26	1.64

are two to three-fold larger than for water at the corresponding temperatures. This can be attributed to the variations in additives composition rather than to the effect of the base oils.

The lubricants were prepared by further dilution of the concentrated emulsions 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.

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 3. 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.

### 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.

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

**Table 3**  
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	<sup>a</sup>	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	<sup>a</sup>	0.99	4.90	1.20	0.31	0.40

<sup>a</sup> Was not measured by optical emission spectroscopy.

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