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"The Effect of Die Lubricant Spray on the Thermal Balance of Dies"

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ABSTRACT:

Until recently little has been published concerning the influence of die lubricants and their application on the thermal balance of die casting dies. Much of this was because of the difficulties in obtaining good information on the heat transfer properties associated with the die lubricant spray and the die casting die.

Using a special simulation program in conjunction with data from lab test equipment and a die casting machine, we have been able to determine the heat transfer coefficients and heat fluxes obtained when spraying die lubricants onto hot dies. This paper describes our results on how different spraying parameters (dilution length, spray angle, air pressure, liquid pressure, etc.) and die lubricant compositions affect the thermal balance of die casting dies based upon the heat fluxes and heat transfer coefficients measured.

Introduction:

The use of water based die lubricants is commonplace in high pressure die casting. They serve many important functions, including releasing parts, lubricating the moving components of the dies, and preventing solder formation. How a die lubricant performs each of these functions is readily measured on the shop floor. One other important function of the die lubricant is the removal of heat from the die and its overall effect on the thermal balance of the die. Unlike the other functions, the effect of die lubricants on the thermal balance of dies is not readily measured or completely understood. A thorough knowledge of how die lubricant chemistry and application variables affect the removal of heat from the die surface will aid a die designer in designing a more thermally balanced die and help the die caster to better maintain thermal balance of the die by controlling process parameters. This should translate to improved part quality and lower manufacturing costs.

The generally accepted model for the removal of heat from a die surface by spraying die lubricant is shown in Figure 1. It shows that the ability to remove heat is influenced by the surface temperature of the die. At low die temperatures the heat flux is low because of the small differential in temperature between the die surface and the die lubricant and the fact that little evaporation of the die lubricant occurs at these low temperatures. As the die temperature increases so does the differential between the temperature of the die and the die lubricant and the rate of evaporation of the die lubricant. This increases the heat flux out of the die. The heat flux continues to increase with increasing temperature until a vapor film begins forming over the surface of the die. This is the burnout temperature. At die temperatures above this, the heat flux decreases, as the die lubricant spray is less able to penetrate the vapor film. The temperature at which the vapor film forms a continuous barrier over the die surface that the die lubricant spray cannot penetrate is called the Leidenfrost temperature. The Leidenfrost temperature is generally accepted to be ca. 360°C.

Research has been done by numerous groups to examine the effects of die lubricant spray on the cooling of dies. The group at Ohio State University used an experimental test stand equipped with thermocouples to measure the cooling effect of various spray parameters when die lubricant was sprayed onto an H-13 steel plate.[1,2] The group at CSIRO and Monash University carried out similar experiments but instead put thermocouples into a die insert to measure the thermal effects under actual die casting conditions.[3] Similar observations and conclusions were made by each group. Basically, the die surface temperature was cooled rapidly. After completion of the spray cycle the surface temperature quickly recovered its original value. Bednareck has taken this type of information further to estimate the relative effect of die lubricant spray on the thermal balance of production dies.[4]

To date there has been no actual correlation of the results obtained in laboratories compared to what is observed in die casting machines run under actual production conditions. Furthermore, the effect of die lubricant composition on the thermal balance of dies has not been investigated. In 1990 Bühler AG, MAGMA GmbH, Wollin GmbH, and Chem-Trend, Incorporated began a research program to better define the effects of various spray parameters and die lubricant compositions on the thermal balance of dies. This project involved developing a sophisticated experimental spray set-up to simulate the die casting process, using a computer modeling program to calculate the heat fluxes from data obtained in the experimental spray set-up, and verifying the modeling and test results in a die casting operation. This paper describes the results of this research, showing how various spray parameters and die lubricant compositions affect the thermal balance of dies. Furthermore, it shows that the experimental protocol and computer modeling techniques are valid for determining heat fluxes that can be used in evaluating die casting processes.

Experimental:

Experimental Spray Set-up A schematic of the set-up is shown in Figure 2. The experimental set-up consisted of a plate of H-13 steel containing numerous thermocouples at various depths and locations. The depths were 1.5mm, 3.5mm, and 35mm. The locations were in the center of the block to measure the heat loss at the area of highest die lubricant spray density and at a given distance (15mm and 25mm) from the center of the block to measure heat loss at a given distance from the area of highest die lubricant spray density. Die lubricant was sprayed through a Wollin automatic spray gun at a measured distance from the die steel. Surface temperatures were measured using an infrared camera. The spray application was performed under a given set of conditions for multiple cycles (up to 100 cycles) and computer controlled to ensure reproducible application of lubricant. Die lubricant was sprayed for a set period of time. Between die spray cycles the steel block was brought into contact with a heated block to simulate contact with molten metal. The data collected throughout all of the spray cycles under a given set of conditions was used to calculate the heat flux.

Computer Simulation An inverse simulation technique program was used to calculate heat fluxes and heat transfer coefficients from the temperature profiles measured in experiments run on the experimental spray set-up. The resultant values for heat fluxes were used to predict the thermal balance obtained in a die casting machine using the MAGMASOFT program.[5,6]

Die Casting Die casting was done in the MAGMA foundry using a fully automatic 630T die casting machine from Bühler AG. In addition to being equipped with an automatic melt supply and extractor, it had an AC Servo SM2024 spray unit from Wollin GmbH. The part being cast was a 210 x 290 x 8mm plate. Thermocouples were placed in the various places of the die at depths of 3mm and 10mm as shown in Figure 3.

Discussion:

The research first focused on measuring die temperatures when die lubricant was sprayed onto a heated H-13 steel surface. In order to obtain accurate and reproducible data which could be related to actual die casting conditions, careful thought had to be given to the design of the experimental apparatus. The experimental spray set-up consisted of a heated plate of H-13 steel, programmable automatic spray equipment, temperature measuring devices, and a computer to record the data (See Figure 2). The heated steel plate contained thermocouples at depths of 1.5mm, 3.5mrn, and 35mrn below the surface. One set of thermocouples was placed in the center of the steel block to measure heat losses at the area of highest die lubricant spray density. This measured the greatest heat losses due to die lubricant. Other sets of thermocouples (at the same depth) were placed at certain distances from the center of the steel block (i.e. in areas of lower die lubricant spray density). The heat losses measured by the thermocouples show how the die lubricant affects the thermal balance of the die in areas peripheral to the area of highest die lubricant spray density. This shows the radial distribution of temperature. This gives an indication of the die lubricant's ability to wet and spread on a die surface. Surface temperatures were measured using an infrared camera shortly before and after spraying die lubricant. The following variables were evaluated using the experimental spray set-up: air pressure, die lubricant pressure, the distance between the end of the spray nozzle and the die surface, spray angle, die lubricant concentration, and the die lubricant formula. The variables and the ranges studied are listed in Table I. When studying one variable, all others were held constant. During

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each study the initial temperature of the H-13 steel plate was varied from 150ºC to 400ºC so that the heat flux could be measured as a function of initial die temperature. This covers the range of initial die temperatures typically experienced in a die casting operation. This allowed the generation of thermal profiles of the die lubricant heat flux at various die temperatures.

Figure 4 shows a typical thermal profile obtained when spraying die lubricant on the hot steel plate. As seen in earlier studies, the temperature of the die steel decreases dramatically upon spraying. As expected, the decrease is most significant with the thermocouple closest to the surface in the center of the spray. The temperatures gradually recover to the original temperature after the spray cycle is complete. This experiment was repeated for many spray cycles in order to calculate the heat flux for a given die lubricant under a given set of conditions. By repeating the measurements at different initial temperatures of die steel, the heat flux of the die lubricant for given die lubricants and spray parameters over a wide range of die temperatures was determined. The resultant heat flux data obtained in a typical series of experiments is shown in Figure 5.

One of the first spray parameters evaluated was the fluid pressure of the die lubricant. Holding all other variables constant, the fluid pressure was changed from 60-90 psi. The heat flux data generated by this series of experiments (Figure 6) showed that at temperatures below 200ºC there was little influence on the heat flux. However, at greater temperatures the heat flux increased with the increased lubricant pressure. This is due to the formation of the vapor film at temperatures above 200ºC. The higher lubricant pressure helps the lubricants better penetrate the vapor film to reach the die surface and improve the heat flux. At the lower temperature little or no vapor film exists; therefore increased lubricant pressure shows no effect in this region. Varying the air pressure used to atomize the spray over the range from 45-90 psi did not affect the heat transfer properties of the die lubricant. The angle of the spray nozzle to the die surface affects the heat flux as shown in Figure 7. The most efficient angle with respect to heat flux is one that is perpendicular to the die surface. Deviating from the perpendicular by 30º and 45º substantially decreases the heat flux due to an increase in die lubricant droplets being deflected from the die surface before significant evaporation can occur. This result differs somewhat from that reported by the group at Ohio State University, which found no effect of spray angle on the heat loss properties of die lubricant spray under the conditions they studied.[1,2]

Another spray variable evaluated was the spray time at a constant die lubricant quantity. This can be obtained simply by changing the orifice size of the spray nozzle . Spraying the same volume of die lubricant in a shorter period of time removes heat faster from dies with high initial temperatures where there is presumably a continuous vapor barrier. At colder die temperatures the high volume spray appears to be less effective than the lower volume spray, due to the run-off of the excess die lubricant. These results are shown in Figure 8, in which the same total volume of die lubricant was sprayed for different time periods.

Varying die lubricant concentration over the range of 1/20 -1/60 dilution length had no effect on the heat flux (Figure 9). This was expected, since only very minor amounts of the die lubricant solids are required to lower the surface tension of water. This reduction in surface tension improves the ability of water to wet and spread on a hot steel surface and therefore remove heat from the surface. Although die lubricant dilution does not affect the heat flux out of the die, it will affect the on-die performance properties of the die lubricant. On-die performance properties depend not only on a good heat flux, but more importantly on the quantity and chemistry of the film of die lubricant solids left on the die surface after the water evaporates.

One important variable that has not been addressed with regard to thermal effects on dies is that of die lubricant composition. Die lubricant composition can have just as strong an influence on the heat flux as the aforementioned spray variables. As mentioned previously, the addition of die lubricant to water reduces the surface tension of water, allowing it to wet and spread more readily on a surface such as a steel die. The lowered surface tension should translate to an improved heat flux by allowing the die lubricant to penetrate the vapor film easier and to wet and spread on a hot surface better once it has penetrated the vapor film. The relative ability of a die lubricant to wet and spread on a die surface and have a high heat flux depends upon the particular chemistry of the die lubricant. Figure 10 shows the heat fluxes for water and three die lubricants all having different chemistries. As one would expect, all three die lubricants show

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better heat transfer properties than water because the die lubricant solids improve the wetting and spreading properties of water. This is particularly true at higher temperatures where the lubricant must penetrate the vapor film. Of particular interest is that die lubricants A & C showed much better heat transfer characteristics at high temperatures than die lubricant B with burn-out temperatures in excess of 250°C initial die temperatures. Compared to die lubricant B, die lubricants A and C are better able to penetrate the vapor film and deposit a lubricant film on hot dies. This is particularly important in that many die lubricant problems are related to high die temperatures at which it is difficult to form a lubricant film on the die.

The cooling effect of the die lubricants can be related to the wetting and spreading properties of the die lubricants. The wetting and spreading properties were determined in two ways. The first was by using high speed photography to photograph the wetting and spreading behavior of the die lubricants as they were sprayed onto the steel plate. Figure 11 shows that at 180°C the products have similar wetting and spreading behavior. Figure 10 shows they have similar cooling characteristics. Photographs of wetting and spreading at 340°C, Figure 12, shows that die lubricants A & C wet better than die lubricant B. This is consistent with the heat flux data at 340°C in Figure 10 . Because photography can be somewhat subjective for measuring wetting and spreading of die lubricants, another method of determining the wetting and spreading characteristics of die lubricants was used. That was to repeatedly spray the die plate at a given initial temperature (250°C) with a given die lubricant. Infrared photographs were taken of the die surface before and after spray application of die lubricant. Any die lubricant film deposit on the steel surface would change its emissivity. After reheating the die plate back to its initial temperature as measured by a pyrometer, another infrared photograph was taken and subtracted from the original photograph. The resulting differences in apparent surface temperature was actually a difference in emissivity due to presence of a lubricant film on the die surface. Using this technique, die lubricant C wet and spread over a larger area than die lubricant B (Figures l3A and l3B) and is consistent with the photographs in Figure 12 and the heat flux data in Figure 10. Knowing that different die lubricant chemistries affect the thermal balance of dies differently, particularly at temperatures above the burn-out temperature, opens up a number of possibilities for die casting using high die temperatures. It could allow the die caster to select the proper lubricant in order to decrease cycle times and run hotter dies without excess solder formation.

Up to now the only data that has been presented has been obtained on an experimental spray set-up and not on a die casting machine under actual die casting conditions. In order to see if the data measured on the spray set-up and the heat flux data calculated using the inverse simulation techniques on the computer were valid, parts were die cast in the MAGMA Foundry using a Buhler 630T die casting machine equipped with a Wollin spray unit (Figure 14). The part was a metal plate (210 x 290 x l8mm). Thermocouples were placed in the die at various positions and at various depths (Figure 3). Using the heat fluxes calculated from the data obtained in the experimental spray set-up and knowing the die casting conditions under which the parts would be made, the temperatures measured by each of the thermocouples in the die over numerous casting cycles were predicted using the MAGMASOFT computer program. The calculated temperatures are in close agreement with the actual temperatures measured through many die casting cycles (Figure 15). Therefore, the data measured on the experimental spray set-up and the heat fluxes calculated from the data give results that are representative of the true die casting process. The effects of the spray parameters on the thermal heat flux are translatable to how die lubricants and spray parameters influence the thermal balance of die casting dies under actual casting conditions.

Conclusions:

Several key points can be made regarding the effect of die lubricant spray on the thermal balance of dies as determined in this study. These are summarized as follows:

1. Heat fluxes increase with increasing die temperature up to a certain temperature (burn-out temperature) and then decrease as the die temperature increases further until it reaches the Leidenfrost temperature.

2. Increased fluid pressure increases the heat flux particularly at higher die temperatures (above 250°C). Air pressure seems to have no effect over the range studied.

3. The spray gun should be perpendicular to the die surface to gain maximum cooling efficiency from the die lubricant.

4. Die lubricant chemistry affects the cooling of the dies, particularly at elevated temperatures (more than 220°C). Die lubricant dilution did not seem to affect heat flux within the range of dilutions studied.

5. The experimental method used to obtain the heat flux values is valid and translatable to an actual die casting process. This was demonstrated by using the inverse simulation to calculate heat fluxes from the experimental temperature measurements and then accurately predicting the die thermal profile of a die casting operation using the MAGMASOFT program.

The method used to calculate heat fluxes and predict the thermal profile of dies can be a powerful tool for further understanding the thermal balances of the die casting process. Further work remains to be done on optimizing spray and other process variables to maintain the thermal balance of the die and in turn produce high quality parts. In addition, further efforts are in progress to better understand how die lubricant chemistry influences the thermal balance of dies.

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Acknowledgments:

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TABLE I

Variables Evaluated in Experimental Spray

Set-up for Determining Heat Fluxes

Variable	Range
Initial die temperature	150-400ºC
Air pressure	45-90 psi
Die lubricant pressure	60-90 psi
Distance between the end of the spray nozzle and the die surface	40-220mm
Spray angle (deviation from perpendicular to the die surface	0-45º
Spray time	1-4 seconds
Die lubricant concentration	1/20 - 1/60
Die lubricant composition	A, B, C

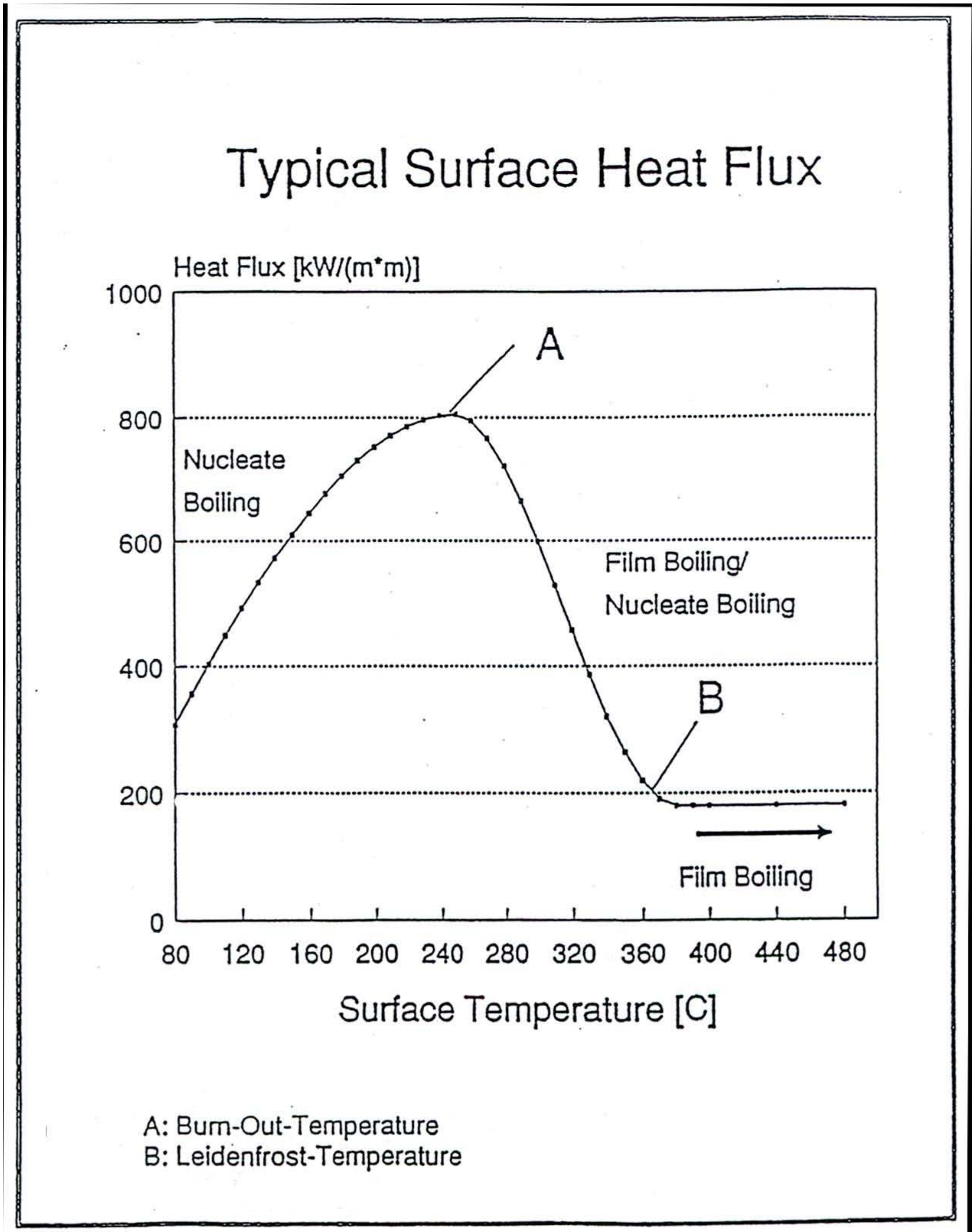
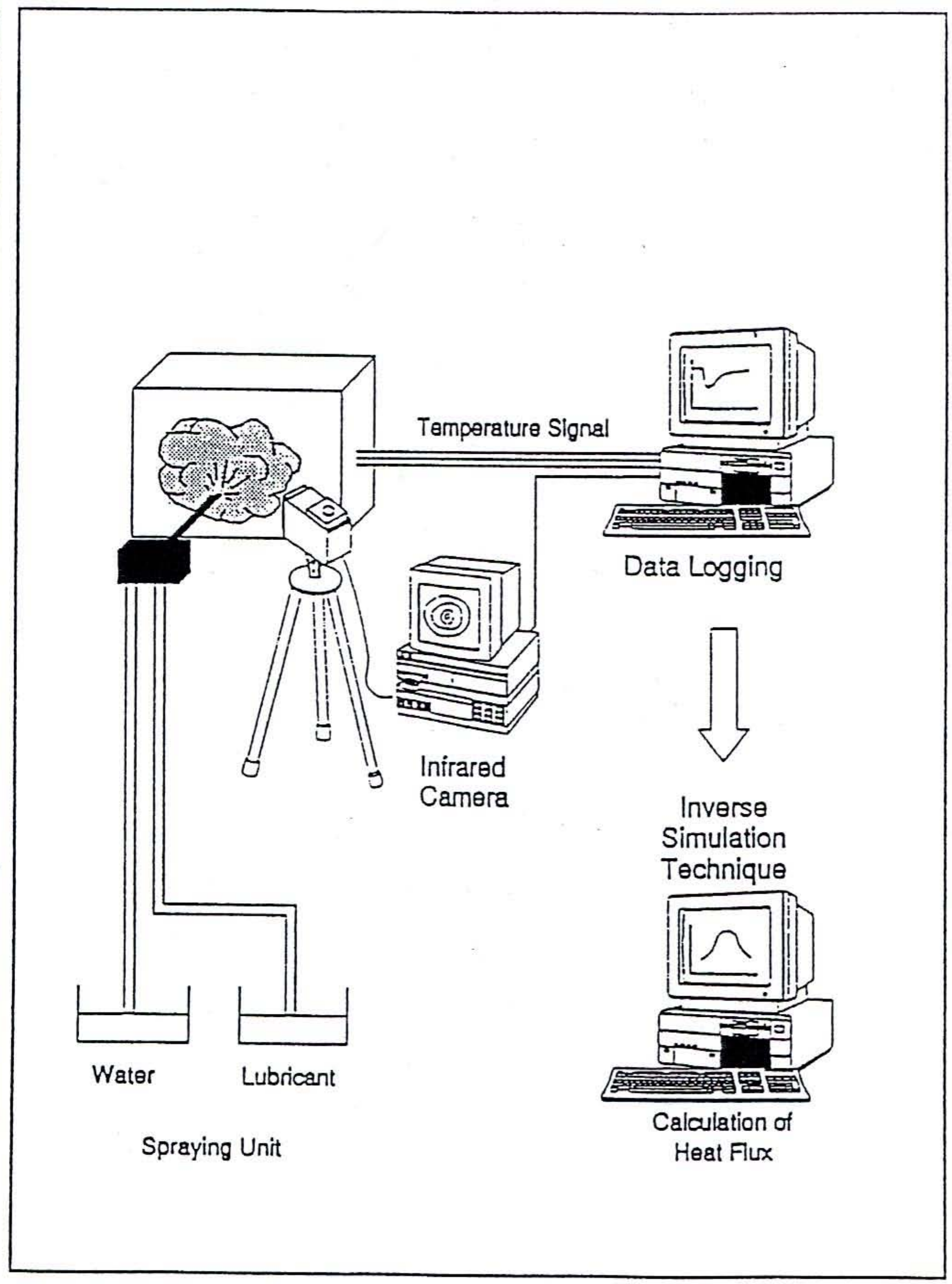


Figure 1. Generally accepted model for removing heat from a die surface with die lubricant spray.



Determination of lubricant characteristics by measuring die temperature with thermocouples, infrared camera and heat transfer calculated by inverse simulation technique.

Figure 2: Schematic drawing of the experimental spray setup for measuring die temperatures and calculating heat fluxes.

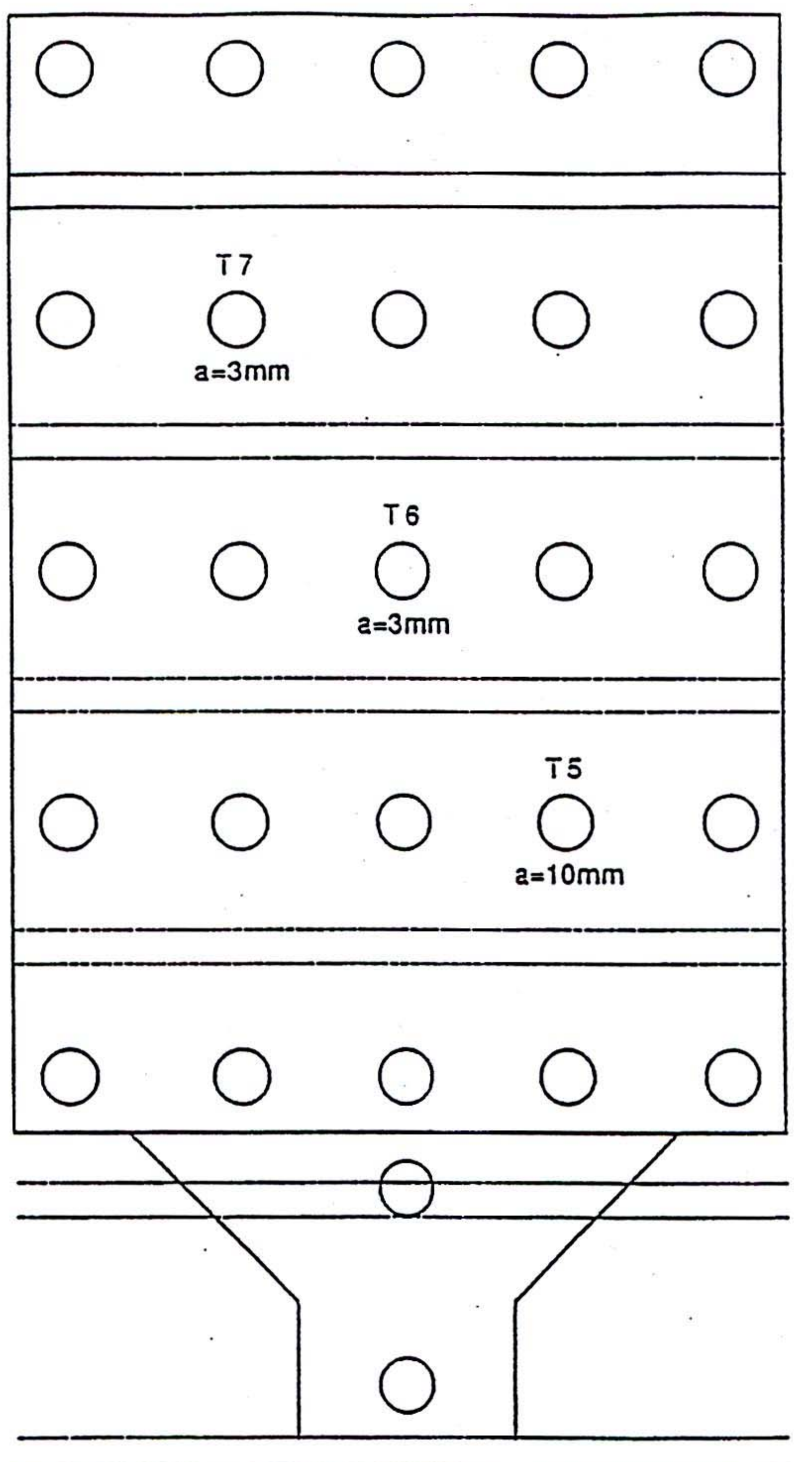


Figure 3: Diagram of the die used to verify the results of the heat Flux measurements and calculations. The positions and Depths of three thermocouples, T5, T6 and T7 are shown.

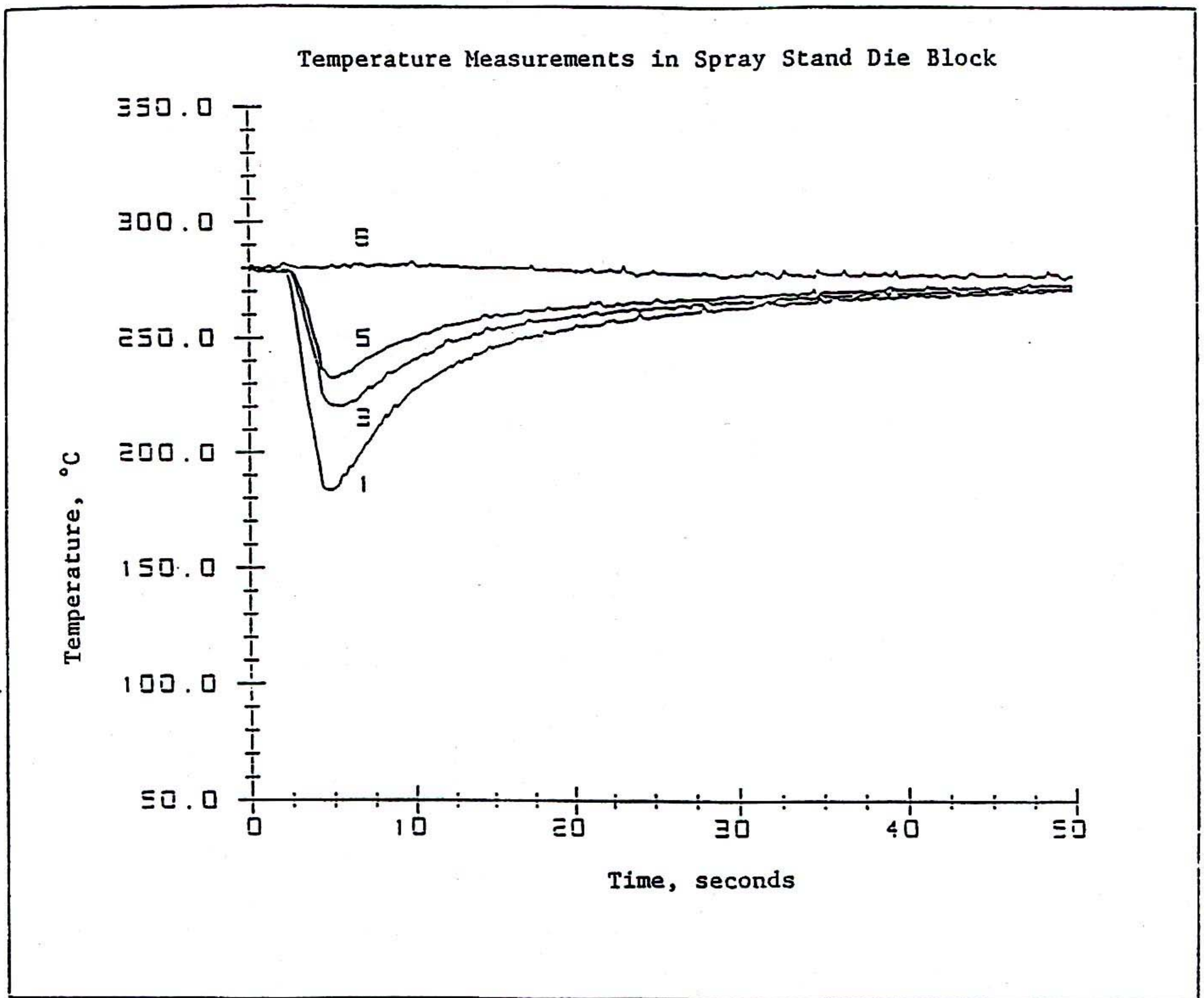


Figure 4: Temperature curves for four thermocouples in the H-13 die block of the experimental spray stand. Thermocouples 1, 3, and 5 are at a depth of 1.5mm under the steel surface with 1 being in the center and 3 and 5 being out of the spray center 15mm and 25mm, respectively. Thermocouple 8 is located in the spray center at a depth of 35mm under the steel surface.

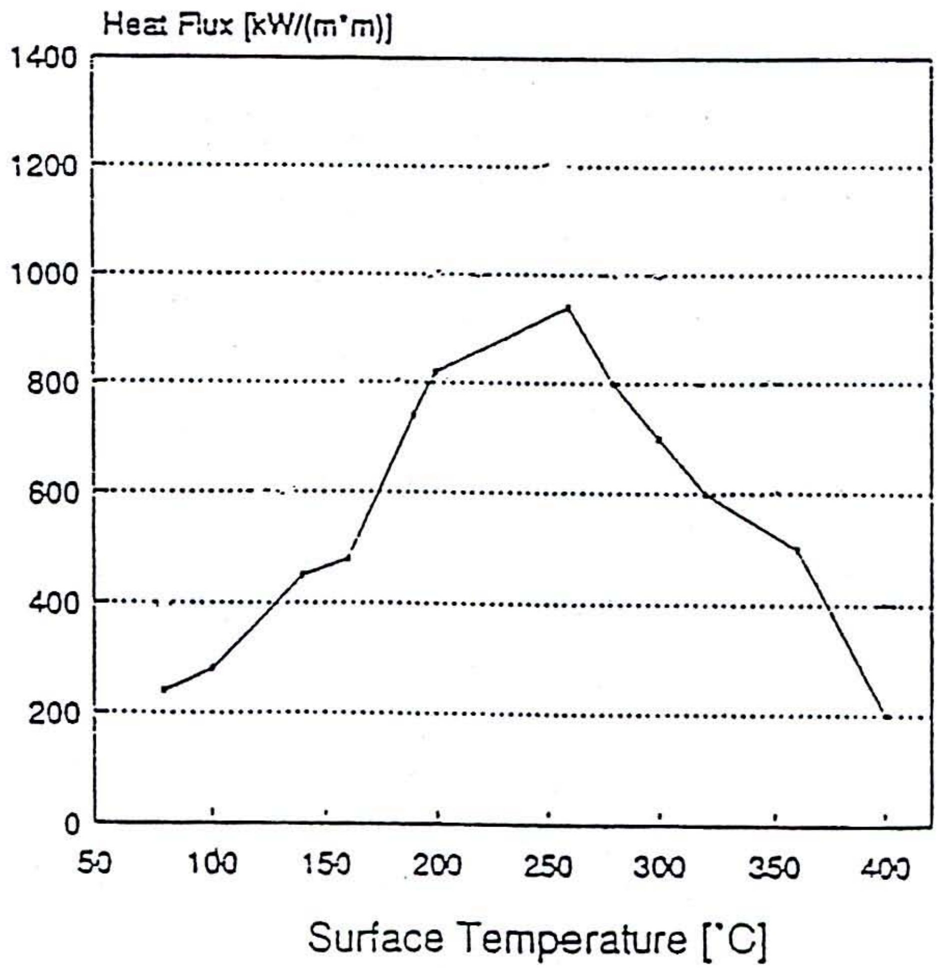


Figure 5: Typical curve of heat flux as a function of die surface temperature for die lubricant sprayed onto H-13 steel.

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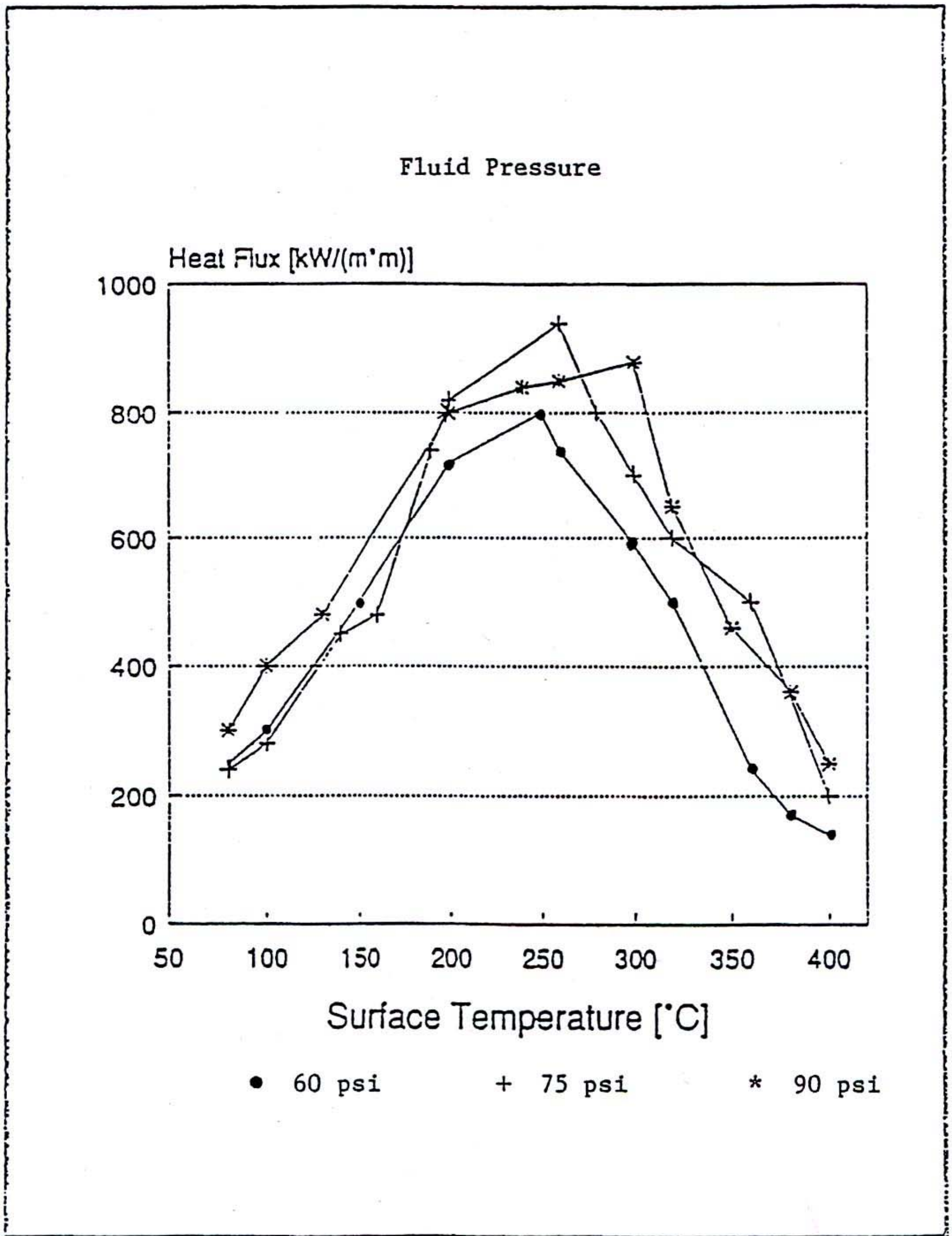

Figure 6: The influence of die lubricant fluid pressure on the heat flux as a function of die surface temperature.

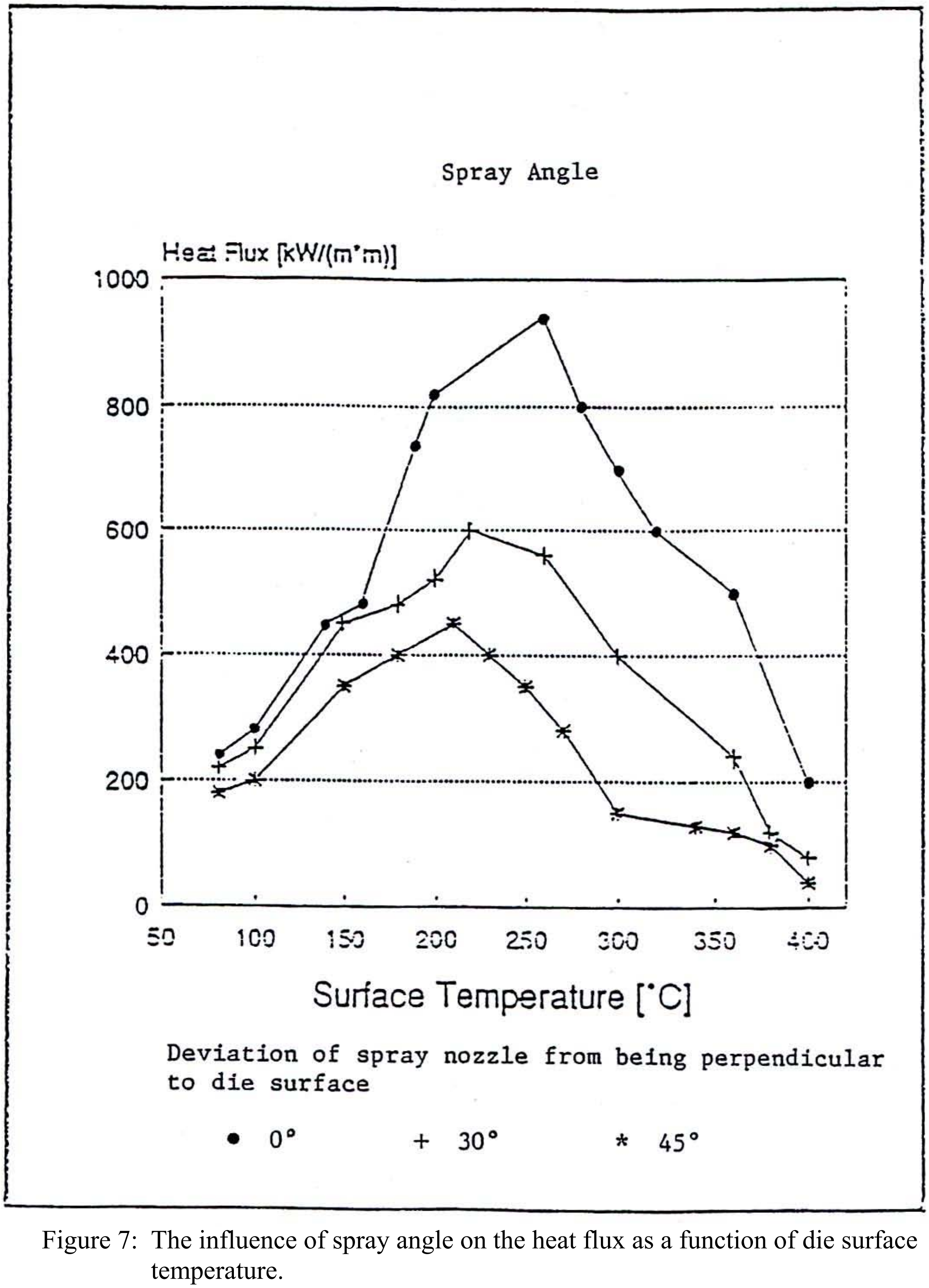

Figure 7: The influence of spray angle on the heat flux as a function of die surface temperature.

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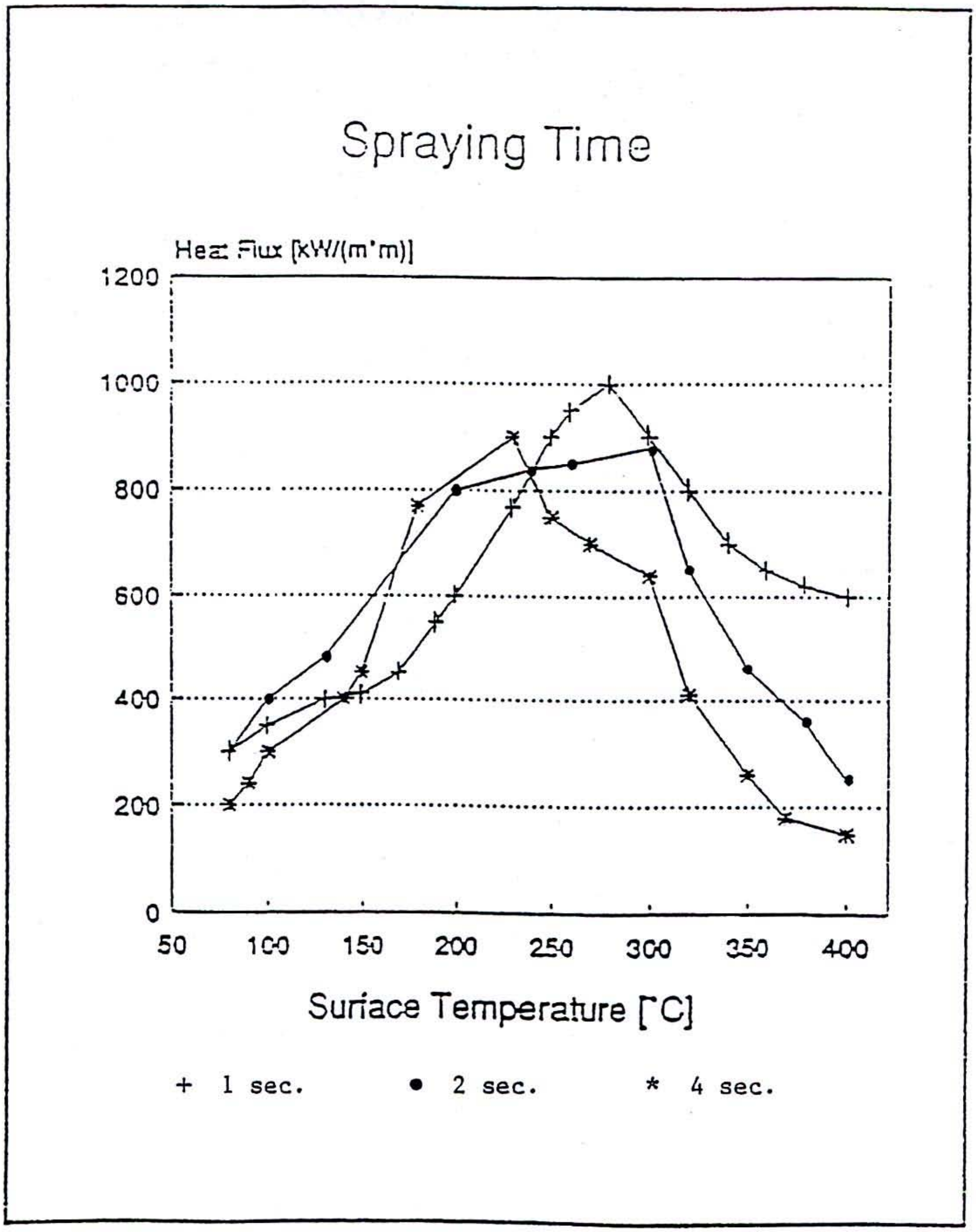

Figure 8: The influence of die lubricant spray density on the heat flux as a function of die surface temperature. Seven grams of die lubricant were applied for different spray times: 1, 2, and 4 seconds. The highest spray density is obtained with the one second spray; the lowest spray density if obtained with the four second spray.

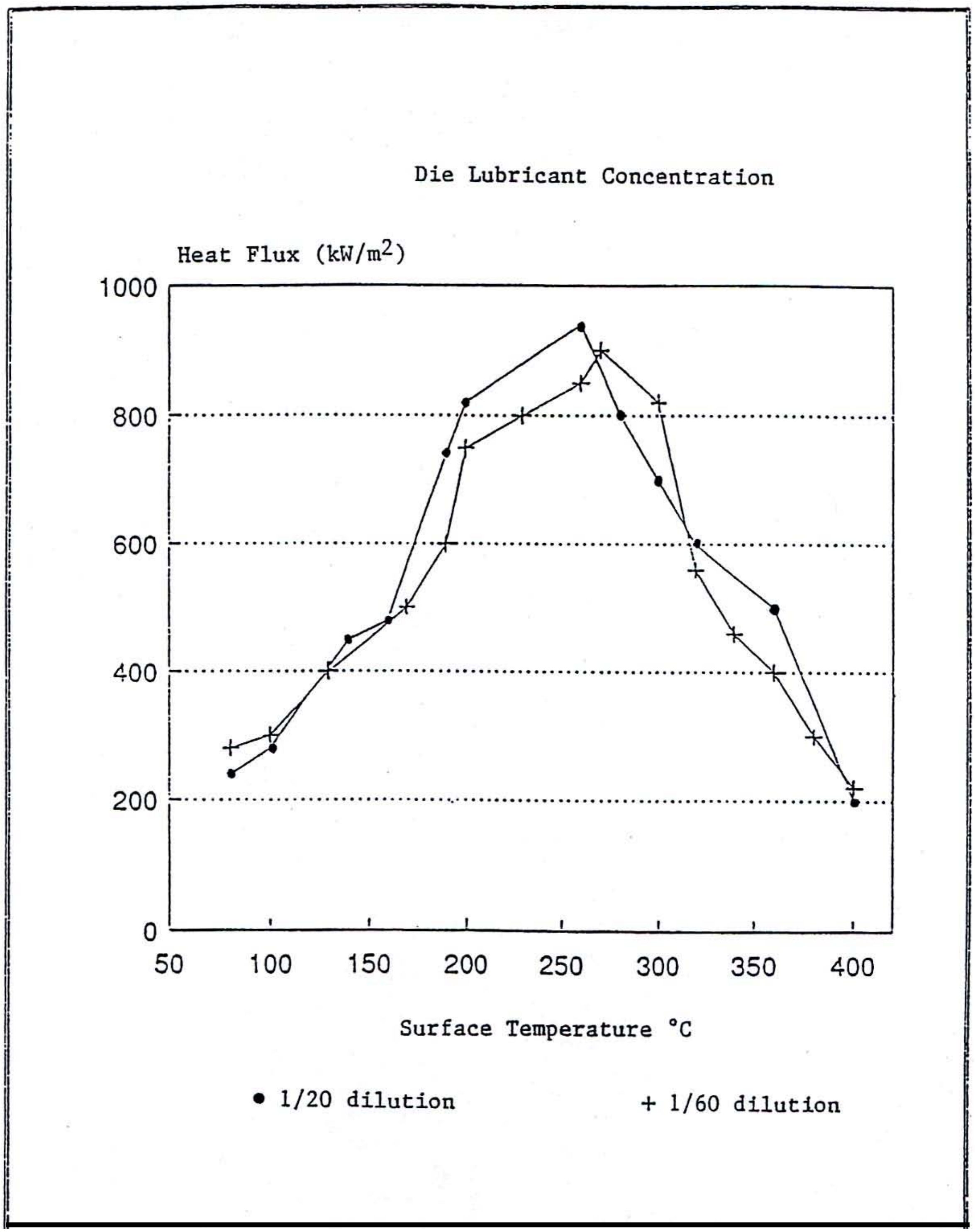

Figure 9: The influence of die lubricant concentration on the heat flux as a function of die surface temperature.

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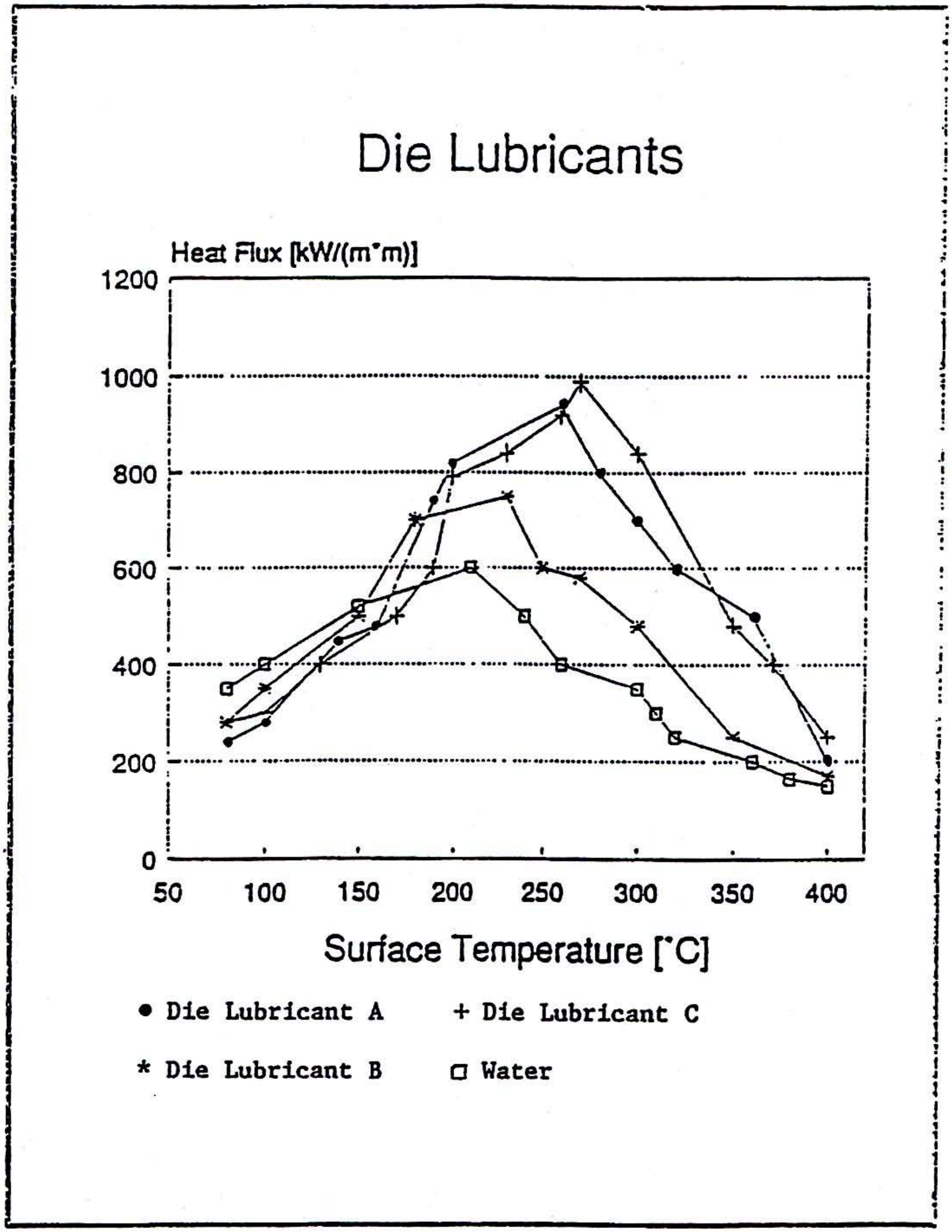

Figure 10: Comparison of heat fluxes for three different die lubricants and water as a function of die surface temperature.

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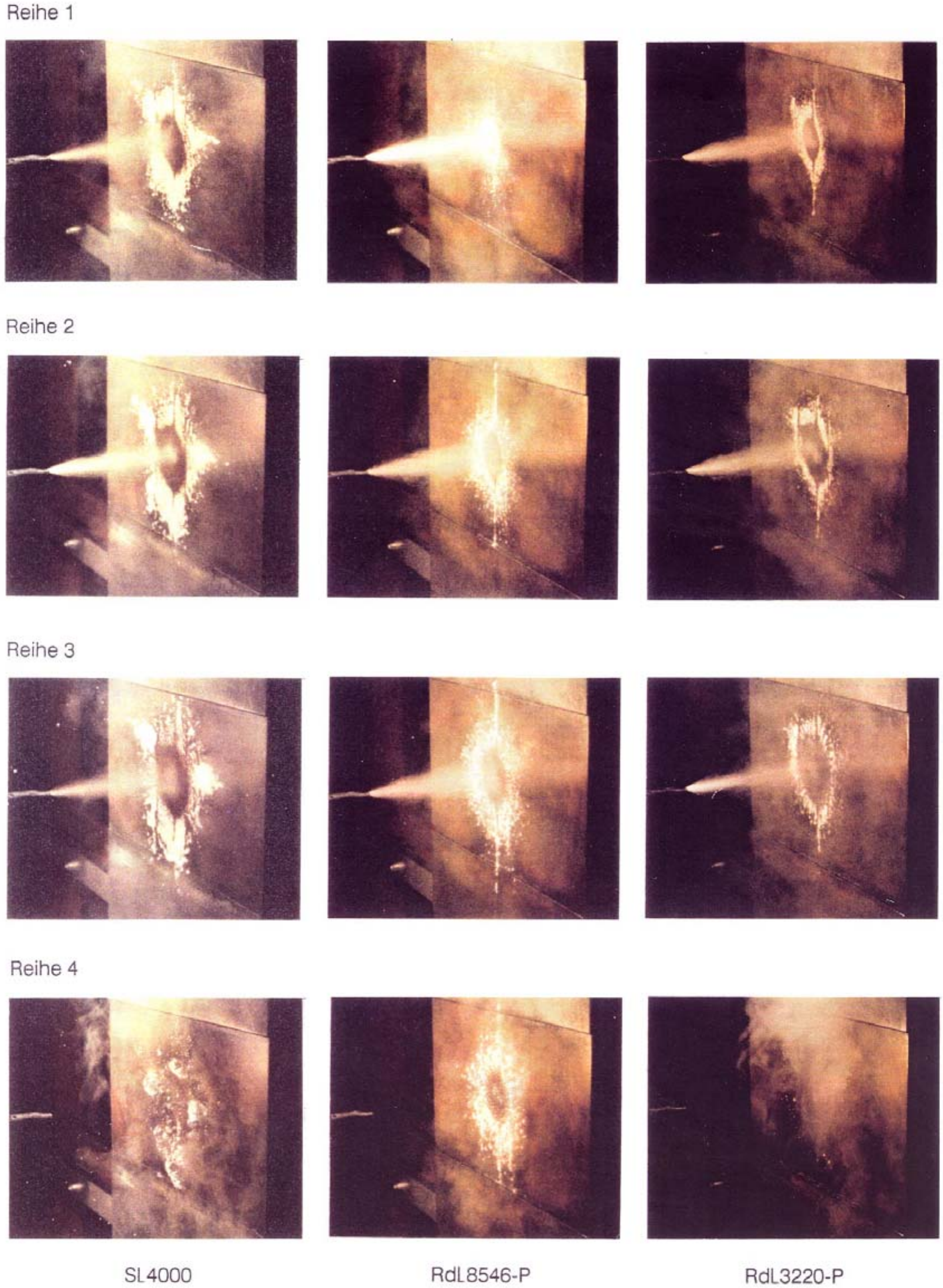

Figure 11: Photographic comparison of three die lubricants during spraying onto die steel. The initial temperature of the die steel was 180ºC. The time between the photographs is 0.6 seconds.

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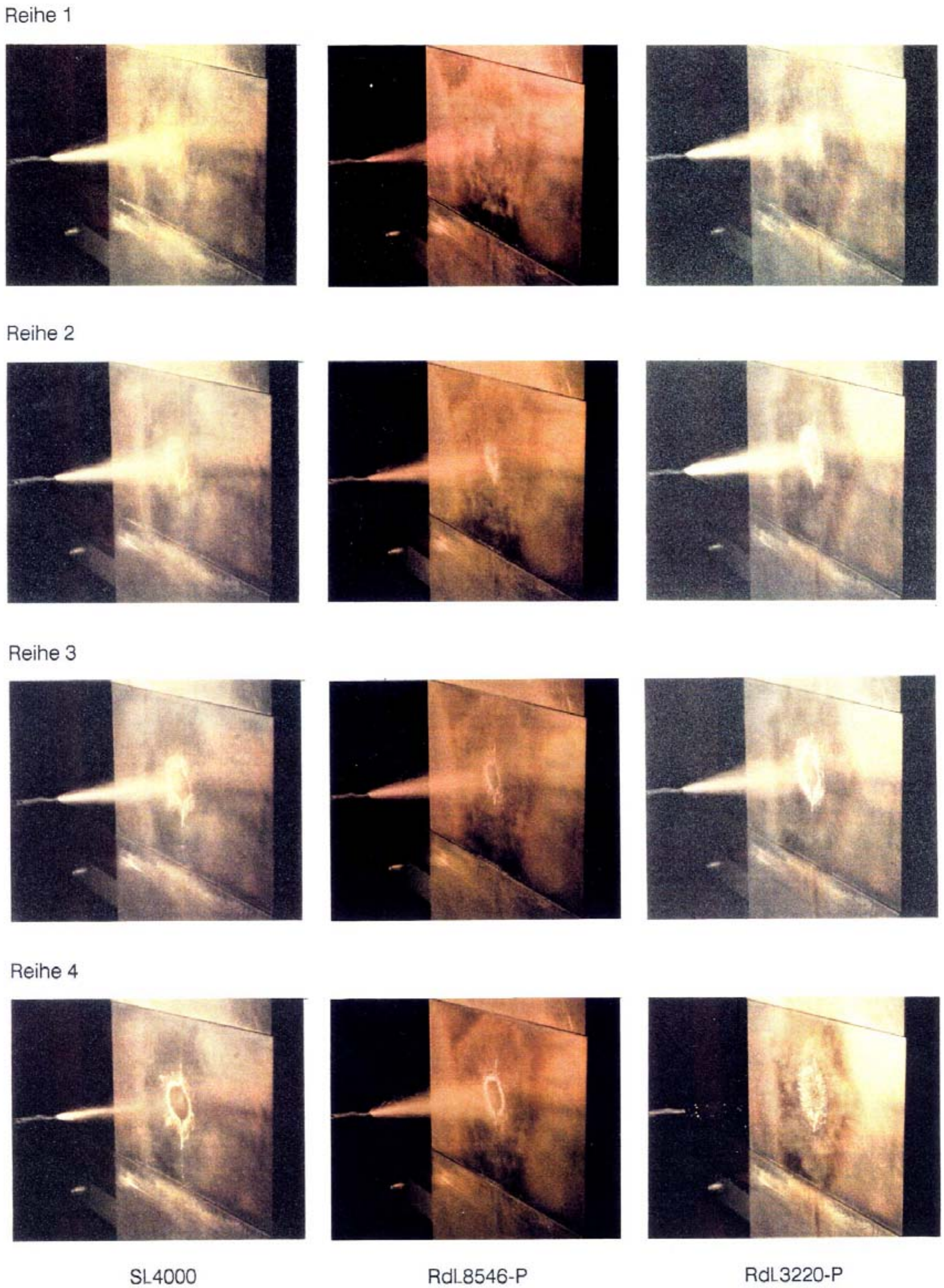

Figure 12: Photographic comparison of three die lubricants during spraying onto die steel. The initial temperature of the die steel was 340ºC. The time between photographs is 0.6 seconds.

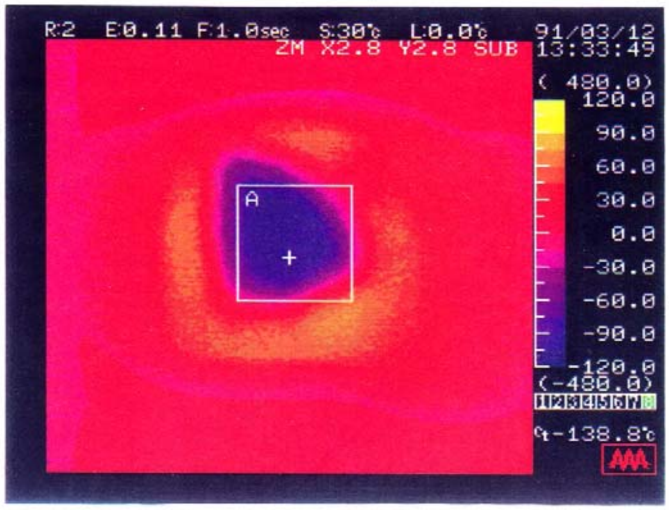

Figure 13A: Thermographical substractive picture for die lubricant C. The initial temperature before spraying was 250ºC.

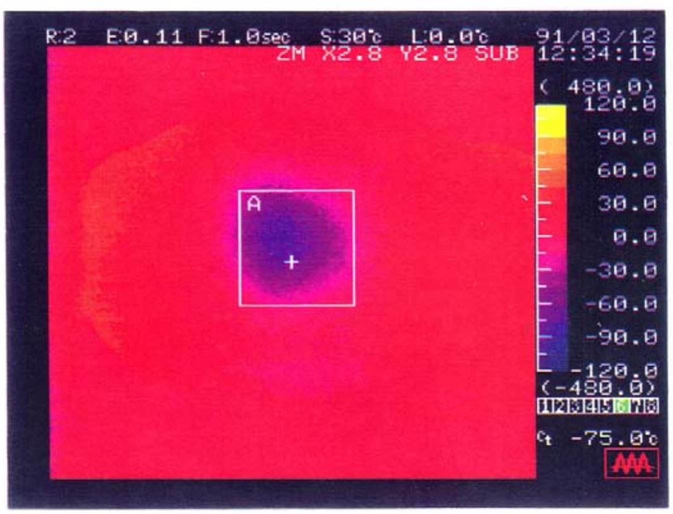

Figure 13B: Thermographical substractive picture for die lubricant B. All spraying parameters and the initial temperature correspond with the p parameters for Figure 13A. The thermographical substractive picture for die lubricant C shows a larger area of temperature differential (i.e. change in emissivity), indicating that die lubricant C wets and spreads better than die lubricant B on 250ºC steel.

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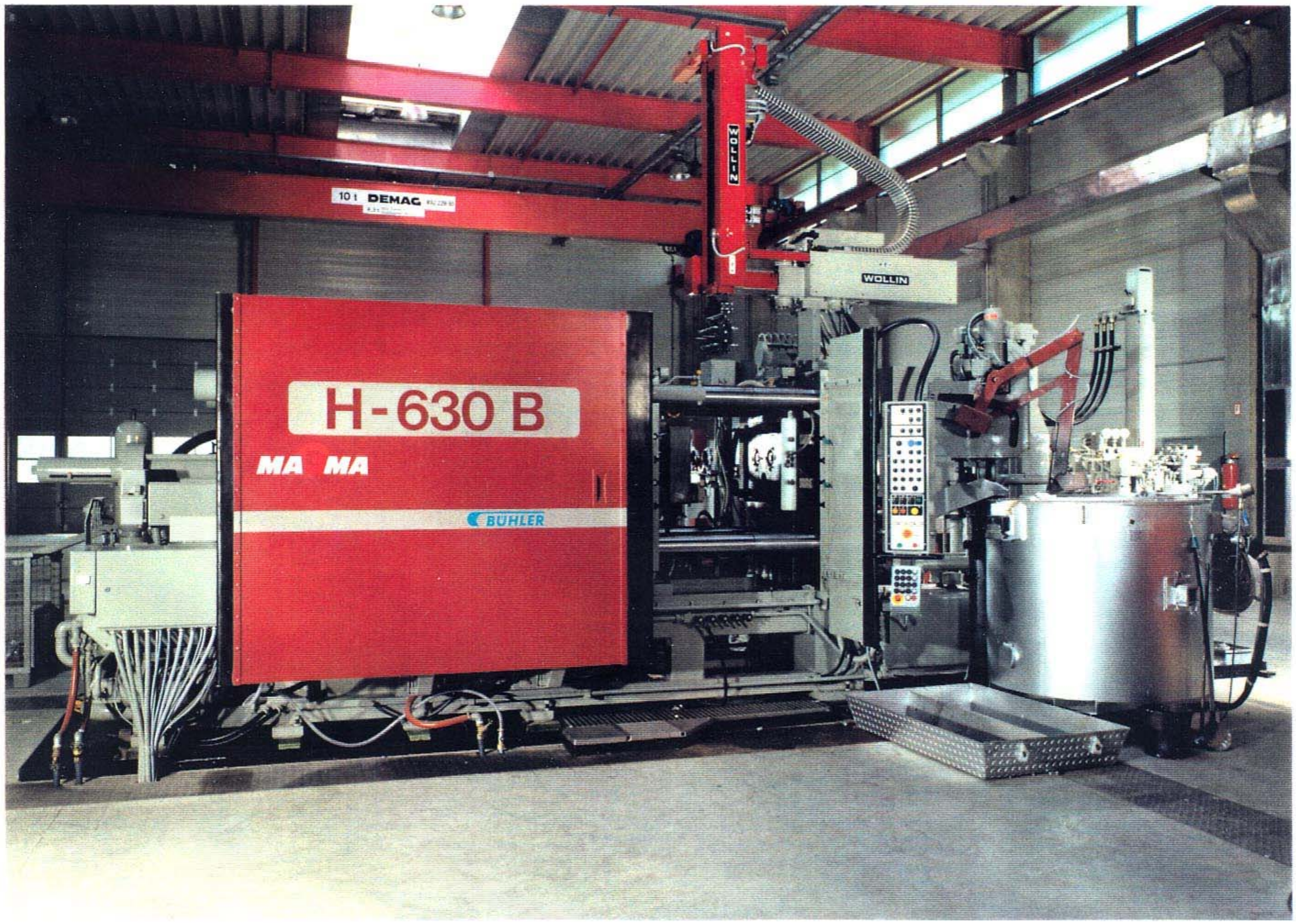

Figure 14: Die casting machine of Buhler GmbH with 630t closing force at MAGMA GmbH. This machine is used for experiments in full automatic production to prove the results taken at the experimental set-up.

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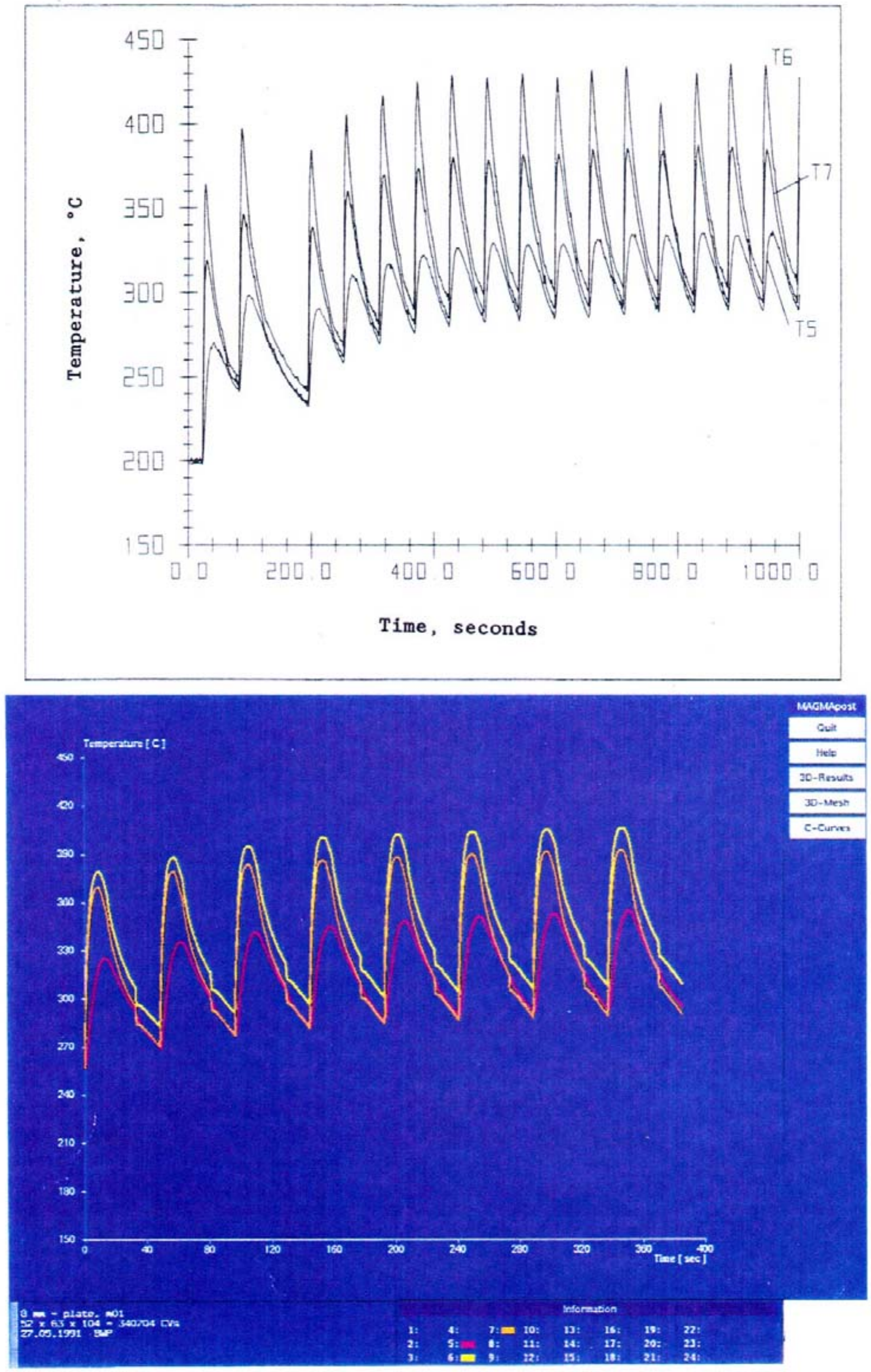

Figure 15: Comparison between the measured temperatures in the die (top) versus the temperatures (bottom) calculated for the die from the heat flux data using MAGMASOFT.

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