Analysis of temperature in different cooling methods

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Abstract. Cooling is one of the main issues in every machining process. By cooling, we can increase the tool life of our tool and maintain the quality of our surface. There are many options in the industry. A wide variety of cooling lubricants are available. There are general requirements for cooling and lubricating fluids used during machining, such as good thermal conductivity, proper lubrication, protection of workpiece and tool against corrosion, anti-foaming or stability during storage and use. These parameters are extremely important for the machining process, so you should be careful when selecting the coolant fluids. In our article we would like to introduce a measurement method, a measuring arrangement, with which we tested many coolant lubricants.

Our main aim will to show that the MQL (Minimum Quantity Lubricant) technology is how better than the other cooling method. We used different types of cooling lubricant. Among our choices are mineral oils, synthetic oils, and biological degradable oils too. We have studied a number of cooling methods, including the Dry lubrication, where lubricant is ambient air, spontaneous emission, induced emission. Doppler cooling with emulsion flood lubrication and molecular feed lubrication, the emissions were spontaneous and induced. Doppler cooling with MQL-molecular oil, here the emissions were the same as by the lubricants. We compare and analyse the results in our article. We tell the measurement parameters and our experiences.

1. Introduction
The lubrication method (MQL) applied during cutting will meet the requirement of minimum quantity lubrication, when the amount of lubricant does not exceed 50 mg per hour [13], occasionally even less than that. The German term MMS for this lubrication method is derived from “Minimal Menge Schmierung”, the English MQL from ‘Minimum Quantity Lubricant’ [1]. MQL is often referred to as semi-dry lubrication [6], or micro lubrication [7]. MQL-lubrication, however, is not a precise term for the lubrication applied with minimum lubricant in everyday practice. Minimum lubrication can be applied for:
- Lubrication of machine and machine parts;
- Machining.

The literature around 2000 frequently mentioned the need to re-examine the multifunctional role of cooling lubricants [1], [2], [9], [11], [12], [13]. The debate was about whether the prevailing system should be developed according to certain functions or whether there should be a total change and the high-speed, high-temperature dry machining, yielding small surface-size chips, should be introduced. Neither the theoretical nor the practical, technological conditions for total change are present yet, but there exists a transitory stage between the two, as shown in figure 1 [3], [9]. Since the reduced amount
of cooling lubricant stands between dry and wet working, attempts have been made to reduce the amount of cooling lubricant. These attempts were successful and the method spread widely within a short period of time (five years). The production technology develops, the new procedures appeared. [5], [8] Today it is called MQL cooling, lubricating. The benefit of the quick success is that less cooling lubricant, which is highly polluting, is being used; the drawback is that studies of the new method have not started. The researchers have been limiting their efforts to trying to find out which one of the cooling lubricants on the market was right for their purposes.

![Figure 1. Cutting temperature change as a function of cutting speed in the case of steel and heavy metal tools](image1)

**Figure 1.** Cutting temperature change as a function of cutting speed in the case of steel and heavy metal tools

1.1. Experimental conditions

Experimental environment: normal ambience DIN 50014 and ISO 554-1970. Climate sign: normal ambience DIN 50014-20/65-1. The experimental protocol is shown in figure 2.

![Figure 2. Experiment guideline](image2)

**Figure 2.** Experiment guideline
The lathe chisel used in the experiments was modified from a CMA brand one-line turning lathe, with the following dimensions:

- top length: 1500 mm
- top height: 250 mm
- revolution range: 16÷2000 min⁻¹
- grading factor: 1.25
- morze: 5
- engine revolution: 1440 min⁻¹
- engine efficiency: 15 kW
- pump efficiency: 0.6 kW
- tool rigidity: 250 N/µm
- vibration: free

1.2. Lubricating processes and the quality requirement of the lubricants used

New terms had to be given to the cooling processes used in the experiments:
- Dry lubrication, where lubricant is ambient air:
  - spontaneous emission;
  - induced emission;
  - Doppler cooling;
- Emulsion flood lubrication;
- Molecular feed lubrication:
  - spontaneous emission;
  - induced emission;
  - Doppler cooling;
- MQL - molecular oil cooling:
  - spontaneous emission;
  - induced emission;
  - Doppler cooling.

1.3. Cooling methods and conditions

Figure 3 shows the measuring circuit. The following cooling methods were used in the measurements:

**Figure 3.** Theoretical design of measurements

**Induced emission cooling:** In this case a lamp was used to produce parallel beams of light. The lamp was attached to a stand on the lathe tool holder. This is shown in figure 5. During Doppler cooling a laser lamp was attached to the lathe tool holder, as shown in figure 4.

**Doppler-cooling:** energy distraction accomplished on an atomic level with lasers (refrigeration). The temperature rises steadily during the friction, with what the moving atoms amplitude is growing, this effect regulate the laser some that the laser brakes the oncoming moving atoms [4], [9], [10], [11].
Figure 4. Use of Doppler cooling

Figure 5. Induced emission cooling

Figure 6. Measurement points

| Experimental data | Technological data |
|-------------------|--------------------|
| Normal ambience DIN50014 and ISO554-1970 | Feed: f(h) = 0.025 mm/rev. |
| feed: f(h) = 0.25 mm/rev. | Feed: f(h) = 0.067 mm/rev. |
| Lathe: HC/TiN, CNMG 1204 08 PF 4015 by DIN/ISO 513 | Grip depth: a(b) = 1 mm |
| Quality of workpiece: 42CrMo4 (matter number: 1,7225) | Revolution: n = 1730 min^{-1} |
| Machine tool: C11A type lathe | |
| MQ-Lubrication applicator: Cobra 2000 | |

| Measuring equipment | Measured data |
|---------------------|---------------|
| Micrometer (range 50-75mm, 75-100mm) | Measurement points 1, 2, 3 |
| Regular slide gauge (1/20 – 150 mm) | D_1[mm], D_2[mm], D_3[mm], |
| Light microscope (for thin sections) | R_α[μm], R_β[μm], R_δ[μm], |
| WA33 (TYP PRLTA13) scales (Precision: 0.001g) | R_γ[μm] |
| Inductive signalling device for measuring revolution (special production) | n[min^{-1}], F_c[N], T[°C] |
| Data collector (Spider8 Control, Carman 4.5 program) GA 300 thermometer | |
| Mitutoyo SJ 201P diamond pointed roughness meter | |
| Photon-electron generating devices | |

| Calculated data | |
|-----------------|-----|
| D_4[mm], V_c[m/min], s[m], | |
| V_f[mm/s], VB[mm], P[kW] | |

After gathering data in the experiments, the results were displayed in a table. These were then plotted in various graphs: R_α - V_f (surface roughness against the amount of chips removed during a period of time), VB - s (back wear against distance), VB - V_f (back wear against the amount of chips removed during a period of time).

Various effects were studied during MQL lubrication at 50 g/hour and 30 g/hour oil consumption. We investigated the viscosity, molecular structure, the effect of application in manipulated and non-manipulated molecular conditions. [9]
1.4. Dry cooling lubrication

Changes in temperature in the cutting zone for the three types of cooling are shown on a bar chart in figure 7.

![Figure 7. Cutting zone's temperature during dry cooling](image)

The highest initial temperature for spontaneous emission is 450ºC. The average temperature is 460ºC, i.e. increasing. The final temperature is 515ºC. In the \( \text{lg} \theta - \text{lg} \ k_c \) coordinate systems the specific cutting energy decreases significantly by 10%. In the case of induced emission, the temperatures were significantly lower (initial: 350ºC, average: 400ºC, final: 470ºC). On the whole, there was a roughly 5% decrease in specific cutting energy.

The most significant temperature decrease was in the case of Doppler cooling (initial: 360ºC, average: 390ºC, final: 420ºC). Even so, the specific cutting energy decreased significantly by about 10%. This change can be explained by the fact that Doppler cooling is controlled, which makes it more intense at the chip base. This is more favourable due to its rigidity. The detachment areas of the material weakness: that is, the thermal plasticity increases, which is also favourable.

| Cooling Type          | Change from Start | \( \Sigma_s \) |
|-----------------------|-------------------|-----------------|
| Spontaneous emission  | \( a_\text{s}=420 \text{m}, \Sigma_s=600 \text{m} \) | \( \Sigma_s=740 \text{ m} \) |
| Induced emission      | \( a_\text{s}=700 \text{m}, \Sigma_s=900 \text{m} \) | \( a_\text{s}=1100 \text{m}, \Sigma=1210 \text{m} \) |
| Doppler cooling       | \( a_\text{s}=700 \text{m}, \Sigma_s=900 \text{m} \) | \( a_\text{s}=1100 \text{m}, \Sigma=1210 \text{m} \) |

1.5. Flooding lubrication

The specific cutting energy change for spontaneous emulsion is shown in figure 8. The concentration of emulsion is 5% by volume. It can be seen in figure 8 that the initial temperature for spontaneous emission is 360ºC with the average being 360ºC. The final temperature rose to 418ºC. The specific cutting energy was reduced significantly by 26%.

![Figure 8. Cutting zone's temperature during 5% volume emulsive cooling](image)

Tool wear:

| Coating Type          | Metal Transfer   | \( a_\text{s}=1100 \text{m}, \Sigma=1210 \text{m} \) |
|-----------------------|------------------|--------------------------------------------------|
| Spontaneous emission  | metal transfer   |                                                 |
| Induced emission      | metal transfer   |                                                 |
| Doppler cooling       | metal transfer   |                                                 |
| Spontaneous emission  | metal transfer   |                                                 |

The average surface coarseness (\( R_a \)) for spontaneous emission improves till \( A_c \) and deteriorates afterwards. The temperature of spontaneous emission used with dry cooling in the cutting zone is approximately 510ºC greater than that of emulsive cooling.
1.6. Non MQL lubrication, non-soluble mineral oil based universal cutting oil
The temperature changes of the cutting zone - under different experimental conditions and cooling methods - are shown in figure 9.

![Figure 9](image)

**Figure 9.** The temperature of the cutting zone in experiments using commercially available, non-MQL lubricant developed, complex cutting oil

Figure 9 show that the highest initial temperature of spontaneous emission (50g/h applied lubricant) is 510ºC with the average being 522ºC. The final temperature is 25ºC. The specific cutting energy remains relatively unchanged.

In the case of induced emission (30g/h applied lubricant) the temperatures dropped significantly compared to spontaneous emission cooling (initial: 336ºC, average: 353ºC, final: 360ºC). The specific cutting energy dropped by roughly 8%.

In the case of induced emission (50g/h applied lubricant) the temperatures dropped significantly compared to spontaneous emission cooling (initial: 331ºC, average: 357ºC, final: 367ºC). The specific cutting energy dropped by roughly 10%.

In the case of Doppler cooling (30g/h applied lubricant) the temperatures dropped significantly compared to spontaneous emission cooling (initial: 335ºC, average: 35ºC, final: 387ºC). The specific cutting energy dropped by nearly 29%. (Figure 8/b)

In the case of Doppler cooling (50g/h applied lubricant) the temperatures dropped significantly compared to spontaneous emission cooling (initial: 335ºC, average: 357ºC, final: 396ºC). The specific cutting energy increased by roughly 2%.

Tool wear:

| Method                      | Increase from Start | Specified Value |
|-----------------------------|---------------------|-----------------|
| Spontaneous emission (50g/h) | increase from start | Σs=510m         |
| Induced emission (30g/h)     | metal transfer      | a_c=400m, Σs=655m |
| Induced emission (50g/h)     | increase from start | Σs=530m         |
| Doppler cooling (30 g/h)     | increase from start | Σs=480m         |
| Doppler cooling (50 g/h)     | metal transfer      | a_c=660m, Σs=680m |

The average surface coarseness (R_a) shows steady improvement for spontaneous and induced cooling (for both 30g/h and 50g/h) and Doppler cooling (30g/h), while Doppler cooling (50g/h) improves till a_c, then suddenly deteriorates. Tool wear is lowest with Doppler cooling (50g/h). On the basis of these results, it is safe to say that in contrast to spontaneous emission there was significant decrease in the cutting zone when induced emission or Doppler cooling was used.

Taking into consideration the amount of lubricant used in the experiments, it can be said that there is little to no temperature difference between the four molecular manipulation tests. It can also be seen that when induced emission cooling was used the average temperature showed only minor changes (approx.: 30ºC).

1.7. MQL lubrication, non-aggregated cutting oil
When the amount of lubricant and the cooling method were changed, the specific cutting energy dropped by 8÷10% with the most significant drop being 30%. Figure 10 shows the results of experiments done with the D model liquid.
In the case of induced emission (30g/h applied lubricant) the temperatures rose compared to the common complex aggregate lubricant oil (initial: 392ºC, average: 443ºC, final: 477ºC). The specific cutting energy dropped by roughly 29%.

In the case of induced emission (50g/h applied lubricant) the temperatures fell compared to the 30g/h applied lubricant experiments (initial: 325ºC, average: 335ºC, final: 343ºC). The specific cutting energy dropped roughly 9%.

In the case of Doppler cooling (30g/h applied lubricant) the temperature values increased significantly (highest initial: 466ºC, average: 493ºC, final: 517ºC). The specific cutting energy dropped by roughly 29%.

Tool wear:
- Induced emission (30g/h) metal transfer $a_c=660m$, $\Sigma s\approx 900m$
- Induced emission (50g/h) metal transfer $a_c=1100m$, $\Sigma s\approx 1450m$
- Doppler cooling (30g/h) increase from start $\Sigma s=760m$
- Doppler cooling (50g/h) increase from start $\Sigma s=780m$

The average surface coarseness ($R_a$) for induced emission (both 30g/h and 50g/h) and Doppler cooling (both 30g/h and 50g/h) shows signs of steady improvement. The specific cutting energy decreases if the amount of applied lubricant is decreased from 50g/h to 30g/h. The surface coarseness slightly improves by increasing cooling lubricant. The lifespan of a tool with induced cooling at 50g/h of applied lubricant proved the best.

1.8. MQL lubrication aggregate cutting oil

The specific cutting energy compared to the D-lubricant was within the margin of error. The results for the series of experiments using E-model fluids are depicted in figure 11.

In the case of Doppler cooling (30g/h applied lubricant) the temperatures showed a slight increase (highest initial: 415ºC, average: 454ºC, final: 526ºC). The specific cutting energy dropped by roughly 32%.

Tool wear:
- Spontaneous emission (50g/h) metal transfer $a_c=660m$, $\Sigma s \approx 880m$
- Doppler cooling (30g/h) metal transfer $a_c=650m$, $\Sigma s \approx 870m$
The average surface coarseness ($R_a$) for spontaneous emission (50g/h) and Doppler cooling (30g/h) improved till $a_c$ and then deteriorated. Tool wear can be delayed by the model liquids and cooling procedures used in the experiments.

2. Conclusions

A modified lathe was used as the equipment for the experiment. The measuring equipment was secured. A parallel light emitting LED lamp was used, as was a small output (P<1mw, 630<λ<680nm) laser and a 'Cobra 2000' drip feeder. A theoretical method based on comparing the kc value of the chips' thickness was created for assessing the experimental results.

It has been proven with in the boundary of the experiment that local cooling can be achieved at a molecular level. Thermoplasticity (reduction of internal friction) and chip base rigidity can be increased by the use of molecules manipulated by induced emission and the Doppler Effect, which is how internal friction can be decreased. The internal stress created by the cutting energy is decreased by 3%. This way the crystallite changes in the layers near the surface become more favourable.

The action mechanism of MQL lubrication has been clarified, and the specific requirement for MQL lubricants has been determined. The surface oil retention ability of coated heavy metals has been examined as have the properties and amounts of the tool wear process.

More research still needs to be done, however. Experiments are being conducted, which are expected to provide more and clearer information on localized cooling. This is why γ-photon experiments have also been added to the programme. More MQL lubricant-specific experiments will be carried out as a result of the current test results.

The results summed up in the article and the results of tests that are currently underway supplement the presently existing knowledge of MQL lubrication, which is important not only for immediate use; it creates the basis for a paradigm shift in cutting technology.

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