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Selected Aspects of Lubrication in Die Forging Processes at Elevated Temperatures—A Review

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Abstract: The paper concerns selected aspects of the application of cooling–lubricating agents as well as methods and devices assigned to lubrication in hot die forging processes realized at elevated and high temperatures in the context of their effect on the quality of the forgings and the durability of the forging instrumentation. An analysis was made of the currently used lubricants and their properties and applications in selected industrial forging processes, and a review was conducted of the presently applied cooling–lubricating systems and devices. The article also presents the authors' own studies referring to the effect of the application of lubricating and cooling agents, the volume of the lubricant portion, the times and directions of its application, and other factors affecting tribological conditions. It also presents lubricating devices constructed based on the knowledge and experience of the authors. The elaborated systems, introduced into selected forging processes, make it possible to examine the effect of the volume and time-frequency of the applied lubricant dose on the wear of the tools and also to select and ensure the optimal tribological conditions in the process with respect to durability. The obtained research results, which were confirmed in the industrial process, indicate the great potential of implementing such devices also in other forging processes because the proposed solutions ensure greater repeatability and stability of working conditions. This increases the efficiency of production and thus significantly reduces the unit production costs, as a two-fold increase (from 8000 to 16,000 forgings) in tool life has been observed.

Keywords: die forging at elevated temperatures; tribological conditions; lubrication; cooling–lubricating devices



Citation: Hawryluk, M.; Dudkiewicz, Ł.; Marzec, J.; Rychlik, M.; Tkocz, R.

Selected Aspects of Lubrication in Die Forging Processes at Elevated Temperatures—A Review. *Lubricants* **2023**, *11*, 206. <https://doi.org/10.3390/lubricants11050206>

Received: 28 March 2023

Revised: 30 April 2023

Accepted: 5 May 2023

Published: 7 May 2023



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1. Introduction

In die forging processes at elevated temperatures, the forging tools, especially their surface layers, are exposed to high simultaneous thermal (from 80 °C to 800 °C) and mechanical (reaching over 1800 MPa) loads [1]. Moreover, the course of such a load exerted onto the forging instrumentation (punches, dies, ejectors, etc.) is cyclic in character. It constitutes a combination of a mechanical and thermal load, which result from contact with and deformation of the hot charge/preform material by the much cooler tools [2]. All this causes the forging tools, especially their surface layers, to be exposed to the operation of many destructive mechanisms, which lowers forging tool durability. In turn, the wear on forging tools negatively affects the changes in the shape of the produced item, and any defects in tool surface (e.g., crack losses) are reflected in the forgings, thus influencing the utility of the produced item. A similar situation takes place at forging units and other auxiliary devices. For this reason, it is very important, during the production process, to control quality aspects not only of the forgings but also of the forging equipment as well as the key technological parameters of the hot die process, such as the tribological conditions, the temperature distributions in the tools and the charge material, and the forging forces.

That is why, in the case of tool durability, an important role is played by lubrication in its general sense, which, in die forging processes, is required in order to minimize friction so that the tool's working impression can be precisely filled by the deformed material and in order to facilitate the removal of the forging from the impression after the process [3].

A special effect on tool durability is exerted by the changeable thermal load, which is the main cause of the formation of fatigue cracks as well as changes in the physical and chemical properties of the surface layer of tool [4]. At the same time, the thermal load affects the intensification of the mechanism of abrasive wear caused by high mechanical pressures [5]. In the typical process of semi-free forging (upsetting, flattening, etc.), lubrication of the tool is not used due to the uncomplicated shape of the deformed material [6]. This is not the case with typical die forging, where lubricant and coolant are required to minimize friction in order to accurately fill the tool cavity with the deformed material. This is because the use of lubricants and cooling agents reduces the friction between the forged material and the tool material and facilitates the release of the product just after forging. It also insulates the tool material (work pattern) from direct contact with the hot forged material. This effectively lowers the die surface temperature, thus reducing the intensity of tempering, oxidation, thermo-mechanical fatigue, and other erosive processes [7]. The disadvantage of lubrication, i.e., the use of lubricants and cooling agents, is the sudden cooling of the surface layer, which can accelerate the process of thermal and thermo-mechanical fatigue [8]. It is assumed that hot forging tools are heated (in their whole volume) to the operating temperature of about 150–250 °C, which constitutes the working temperature of the tools, which, during deformation, rises by a few tens of degrees, asymptotically aiming at equalization during the process and reaching a constant temperature amplitude (forging and lubrication) [9]. Of course, the tool temperature value during forging depends on the amount of the energy provided from the deformed forging, which results from the change of the plastic deformation work into heat, the emission in contact with the hot material and through friction during forming, and from the quality and manner of lubrication [10]. This said, we sometimes observe overheating or cooling of the tools during forging, which points to an insufficiently worked-out technology. In such a case, it is crucial to “steer” the lubrication process, meaning to increase or decrease the lubricant dose or change the lubricating technique [11]. The formation of the lubricating film depends on the spreading of the lubricant droplets (graphite in water) and their drying. Since the drying times are very short, spreading is essentially isothermal. In the paper [12], the authors analyzed the bases of droplet spreading, which was studied using droplet mechanics and principles of similarity. It is assumed that the temperature on the surface of the insert right after deformation equals over 600 °C, whereas right after lubrication, it drops to about 80 °C [13,14]. Such large cyclic temperature changes and gradients inside the tool contribute to thermo-mechanical fatigue and fatigue cracking, which consequently leads to tool damage. A proper selection of the lubrication parameters causes thermal stabilization by lowering the scatter on the contact of heating and cooling of the tools, which ultimately minimizes the occurrence of microcracks leading to tool cracking [15].

For this reason, the lubricating agents aim at effectively lowering the temperature of the die surface, thus reducing the intensity of the tempering, oxidation, and erosion processes [16]. The grease itself should have a high flash point and a sufficiently low dynamic viscosity at the operating temperature. In turn, in the aspect of forging tool durability, it should also protect the forging tools against overheating and thus prevent lowering of the forging temperature (it should have low thermal conductivity). A certain disadvantage of using coolants and lubricants is the rapid cyclical cooling of the surface layer, which may intensify thermal fatigue processes [17]. The usefulness of graphite as a lubricant in warm forging is also affected by the fact that an intensive burn-out of the graphite layer takes place only above 750–800 °C. In turn, other lubricating agents commonly applied in warm and hot forging are molybdenum greases, greases based on graphite, inducing colloidal (graphite with animal tallow), and inorganic boron nitride (and its mixtures), also called white graphite [18].

Apart from the lubrication of the forging tools, sometimes additional lubrication is applied on the surface of the charge material with the use of greases which are easy to remove and by a simple method of their application—by means of brushes or rollers. Additionally, sometimes so-called precoating is used, which consists of covering the charge before forging with a graphite coat and then in the typical lubrication of the dies (through spraying) with an emulsion of graphite powder in oil, water, or a mixture of oil and water [19]. The preliminary coating of the charge with graphite at 100 °C is aimed at reducing the friction coefficient during forging and decarbonizing the forging's surface layer [20]. The main producers of lubricants for the forging industry include Fuchs, Bechem, Henkel, and Naftrtochem [21–26].

Apart from the important properties and other physico-chemical parameters of the lubricants, a key role is also played by the proper manner of lubricant feed as well as its appropriate and uniform distribution, as the correctness of the given plastic forming process is affected by tribological conditions, which largely depend on the lubrication.

The literature provides research studies referring to lubrication in die forging processes [27–29]. The work [21] presents the results of an international project connected with the elaboration of environment-friendly lubricating agents and devices for the lubrication of forging tools used in warm forging of steel. In turn, the study [15] presents advanced tool materials and lubrication devices aimed at reducing die wear in warm and hot forging processes. The work [17] discusses problems with conventional lubrication methods, which can be eliminated by means of automated dosing stations based on PLC (programmable logic controller) drivers. There are also studies in which the authors indicate the possibility of using surface engineering techniques to reduce friction and thus provide “better” tribological conditions. For example, gas or plasma nitriding of tool steel is very common to increase the life of hot forming tools. Nitriding can increase surface hardness and wear and corrosion resistance of forging dies [30]. Generating inherent compressive stress can reduce the tendency of crack formation and increase fatigue strength, and it also has a positive effect on reducing friction, thereby increasing the durability of forging equipment [31]. Similarly, the use of hybrid layers on forging tools has a positive effect on reducing friction and increasing lubricity [32]. In the work [33], the friction and wear characteristics of plasma nitrided and surface-coated tool steel (CrN and TiAlN), while sliding on AISI52100 bearing steel at room temperature and 400 °C, respectively, using a machine with a ball on a disc, were investigated. The results showed that at 400 °C for the CrN coating, compared to room temperature, the friction slightly decreased, but transfer of the bearing steel to the CrN-coated disc, i.e., adhesive wear, was observed. On the other hand, for the TiAlN coating, at the temperature of 400 °C, the friction was very high and unstable and caused an increase in adhesive friction—the transfer of the TiAlN coating to the cooperating ball. In the work [34], an extensive review of the state of the art methods in the area of surface texturing in combination with the use of solid lubricants, including soft metals, diamond-like carbon, and 2D-layered materials, was made because through their synergy, significant reductions in friction and wear in dry conditions can be obtained. In turn, in [35], a new approach was proposed for reducing friction and energy consumption through the so-called limited supply of lubricant (LLS) with adjusted dosing. A special test rig with an optical slider bearing was built, which revealed certain features of LLS lubrication in the cylinder-disc contact and enabled the authors to propose two patterns of wettability gradient, namely belt wettability and interlaced wettability, in order to regulate the supply of lubricant to improve the lubricating properties of LLS. Papers [36,37] presented the results of comparative studies in which surface treatment with shot peening was used to obtain improved tribological properties in comparison with machined die surfaces. Forging dies were subjected to rotation and mechanical shot peening using different media, thus creating matrix surfaces with different topographies. The tribological properties of the surface of the forged dies were analyzed in ring compression tests in dry conditions and lubricated with water graphite grease. The lowest friction was detected under lubrication conditions for turned surfaces with slightly increased roughness compared to the initial

smooth, unmachined die surfaces. Similar studies were carried out in work [38]; non-laser smooth surfaces were made, which were prepared using laser texturing technology on the surface of hot forging tools. Three representative unit angles were identified on the surface of hot forging tools. The results showed that the smaller the angle of the non-smooth unit, the greater the wear resistance of the non-smooth surface. This was clearly proven to provide the best wear resistance and longest tool life for hot forging at 0° . In the literature on the subject, you can find works on the study of drops hitting a dry surface or a layer of liquid (lubricating film), which are of great interest, and while these are not direct studies on lubrication and lubricants and coolants used in hot die forging, they can still be used in this area. For example, in paper [39], a simulation study of the collision of drops with a moving layer at different angles of incidence was carried out using spray cooling. Scientists, using numerical modeling and tests in laboratory conditions covering the issues of fluid mechanics, focus their research mainly on the effect caused by the angle of incidence of the drop. They considered the impact of drops in the normal direction [40,41] and oblique angles [42,43] because different cooling characteristics are obtained in each case. The thickness of the lubricating film layer in practical applications is also crucial in this aspect because droplets hitting a thin layer of liquid react more violently and probably break. In the case of deep cavities or cavities, the critical angle of fragmentation is large, and the generation of secondary droplets is difficult [44]. The heat exchange effect is also influenced by the angle of incidence, where the local maximum of the heat flux moves downwards with the increase in the angle of incidence, and the smaller the layer thickness ratio, the greater the maximum heat flux [45]. The research presented above is important, but in these works, there is no direct verification in industrial conditions, particularly in hot die forging processes.

In order to choose the appropriate tribological system/device before implementing it in industrial forging operation, special tribometers are applied to characterize the performance of the real tribological conditions. This is similar to determining the coefficient of friction in various tests [46,47]. This is important because in the case of forging processes, we are dealing with very high pressures, sometimes reaching even 2000 MPa, which is why the selection of the testing method itself is very important. Unfortunately, most of the available tribometers give the possibility of obtaining low pressure values—up to a dozen or so MPa. Therefore, when using typical tribometers, one should be aware that the load conditions are definitely underestimated. Therefore, it is important to consider the impact of all parameters on the overall process and identify those necessary to reproduce the application [48]. The work [49] indicated the need to consider not only the tribological loads when designing these tribometric tests, which is typical for existing methodologies, but also the specific properties of the process and lubricant. The research specifically concerned the aspect of lubricant leakage from the contact zone, which takes place in drop forging. Therefore, the tribometer test must be specifically designed to reproduce the contact kinematics of the industrial forging operation under test. In the work [50], the authors presented a solution based on the pulley-treadmill method, which provides a rotary-sliding movement. Additionally, the stand has the ability to heat elements to a temperature of 750°C and control it using a pyrometer. The work [51] describes a stand called Warm Hot Upsetting Sliding Test, in which the contact of the forging with the die between the cylinder-shaped sample heated to 1100°C and the penetrator pressed against it at 200°C is mapped. The stand allows for the influence of lubrication to be considered during the tests. Before the test, the samples are covered with a layer of lubricant in the form of graphite with water, and factors such as the thickness of the lubricant layer or the size of solid particles are one of the test parameters. The work [52] describes a solution in which the authors decided to use the pin on the raceway method. A pin with a diameter of 15 mm, which is the equivalent of a matrix, is pressed with a force of 200 N to a rotating raceway, which is heated using the phenomenon of electromagnetic induction. In the work [53], the authors decided to use a ring-pin friction pair. The element imitating the matrix in this solution is a rotating ring of a special design, against which a fixed mandrel

is pressed, which is the equivalent of a forging. Notably, in the work [54], the authors developed a special TriboForge friction test stand, which, unlike classic tribometers, allows for wear analysis under high pressure conditions (300 MPa), i.e., in conditions similar to those prevailing in industrial forging processes.

An analysis of the literature points to many solutions (from common manual methods to automated methods) for reducing the friction and stabilizing the process temperature [55–57]. It should, however, be clearly stated that, at present, the most popular lubrication method is still a manual technique implemented by the operator, which unfortunately often causes non-uniform and nonrepeatable distribution of the lubricating agents as well as a change in the tribological conditions, which negatively affects the wear of the forging tools and the quality of the forging. At present, in the case of so-called transfer presses, we can achieve automated lubrication systems and devices, which are synchronized with the work of the forging units and the whole work center. In turn, in the case of the most typical forging aggregates, i.e., presses and hammers, old, often not very repeatable or reliable lubricating devices are used, which are handled by experienced yet subjective operators. Today, many die forges still commonly use non-automated, low-repeat lubrication devices operated manually by operators. For this reason, the use of more or less automated lubrication and cooling devices and systems is increasingly adopted, which allow for precise dosing of the lubricant [58,59]. Proper lubrication not only determines whether a forging without defects such as underfilling will be produced but also has the advantage of reducing tool wear [60,61]. The intensive development of automation is conducive to the development of new solutions that enable a more precise and accurate deposition of the lubricating material [62], thus increasing the efficiency and shortening the time of lubricant application using a system of multiple nozzles that break up the lubricant in the tool cavity when changing the feed material. In most cases, the design of nozzles depends on parameters such as the lubricant itself, the volume and viscosity of the lubricant, spray pressure, etc. The advantage of nozzle solutions is the ease of directing the lubricant stream and the formation of a thin insulating layer on the surface of the tool. The leading producers of automated lubricating systems based on [63–66] include Jerko (Kempen Germany), AED (Acheson Engineering Dornstadt Automation, Dornstadt, Germany), SMS Group (Düsseldorf, Niemcy), Renite (Chasse-sur-Rhône, France), Spray (Decatur, IL, USA) and Industrial Innovative (Grandville, MI, USA). Figure 1 shows exemplary AED Automation devices mounted on robots and manipulators (Figure 1a) and the solution repeatedly and successfully implemented at German forges proposed by Jerko (Figure 1b).

In the AED solution, due to the use of manipulator arms (Figure 1a), all key parameters during lubrication are controlled, i.e., the position of the nozzle, application times, and proportions of lubricants. At the same time, this results in relatively high investment costs, and the gain from product quality or tool life may not be compensated. In turn, in the case of Jerko, the system allows the nozzle to be attached to a panel inserted under the press/hammer table. The system allows you to program a selection of nozzles to be active or not during the lubrication process (Figure 1b). In both cases, they are highly efficient and precise systems, which, unfortunately, due to their high price and an often-complicated construction (but also reliability), are more often used in cold forging, where the operation conditions are entirely different than in the case of hot forging. Nonetheless, the economy is increasingly enabling die forges that accomplish processes at elevated temperatures to be available.

As was demonstrated above, proper lubrication determines not only the creation of a forging without defects, such as underfills or laps, but it also, in the long run, affects the performance time of the tools, which translates to measurable economical aspects and cost-effectiveness of the forging process. For this reason, there is a search for new solutions referring to both lubricating agents and cooling–lubricating devices ensuring optimal tribological conditions, dedicated to a given industrial forging process. Constant technological progress means that, apart from research centers, in the very competitive

market of lubricants, you can find more and more studies and industrial applications related to lubricants dedicated to specific processes. It should be emphasized that in the case of lubricants, it is difficult to find research papers on their properties, application, and use in die forging processes. In the market, as shown above, there are many companies dealing in the distribution of lubricants, but usually their compositions are kept confidential, and their usability is most often tested in selected forges, which also do not want to boast of test results. Similarly, in the case of research on technical solutions or lubrication devices used in hot die forging processes, it is difficult to find studies. In contrast, most companies that develop such solutions do not share the results of research but boast about such devices on their websites and information brochures. In addition, it should be emphasized that such commercial solutions are relatively expensive (several tens of thousands of euros) and, after their implementation in the forge, it is difficult to modernize and expand them. As a result, their availability for many die forges is limited due to the price, ease of expansion, and the ability to adapt to other forging processes carried out by these forges. The introduction of new devices and technologies is an incentive for further intensive R&D works, presented by authors [55,67,68], and is thus also a constant source of development of the lubrication technology in many aspects of die forging processes at elevated temperatures. Such works allow for an in-depth analysis of tribological conditions in die forging processes and the development of lubricating devices that are competitive in terms of price and operational reliability to expensive commercial solutions.

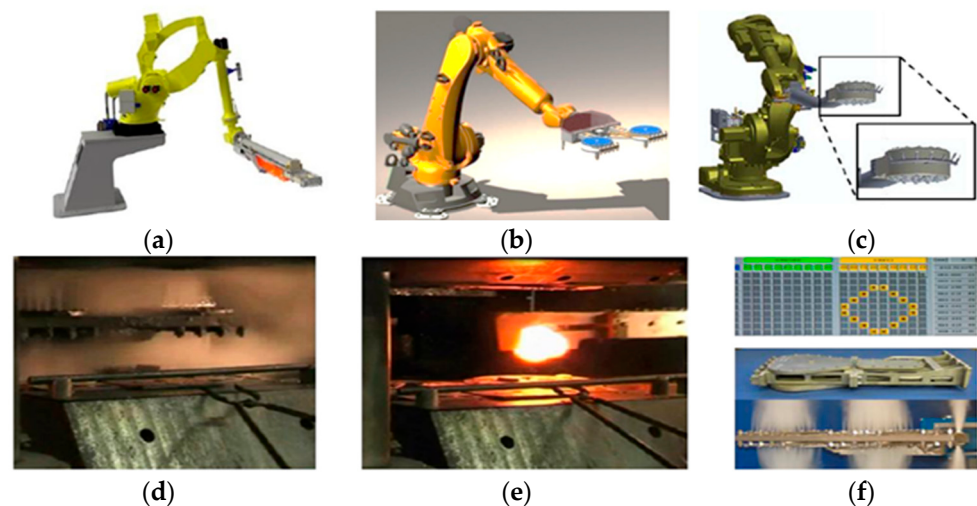


Figure 1. Examples of lubricating system solutions: (a) with the use of manipulators and blow-out of scale [56], (b) with possibility of simultaneous lubrication both dies—preliminary and finishing, (c) simultaneous lubrication of the upper and lower tool, (d) a mobile insertable plate with the option of predefining the lubricating openings—entry of the lubricating plate and start of lubrication, (e) view of a manipulator with a gripper inserting a preform [65], and (f) panel of the lubricating device with a system of active (selected) nozzles.

2. Test Subject and Methodology

The goal of the work is to present the authors' own research related to lubrication in die forging processes. The research was divided into two main stages.

The first stage presents the results of many comprehensive studies carried out in the field of analysis of changes in tribological conditions resulting from the method and quality of lubrication in die forging processes. In the second stage, developed and built lubrication and cooling systems are presented along with their verification of correct operation.

The following main research methods and devices were used in the research:

- Measurements of temperature changes with the thermal camera (FLIR T540 camera, FLIR Systems, Inc. Wilsonville, OR, USA) and a pyrometer with a type K thermocouple (Testo 850 pyrometer, Testo Poland, Pruszkow, Poland);

- The UniTest measuring system for measurement temperatures in time function;
- Numerical modeling using Forge 3.0 NxT software (Transvalor, Biot, France);
- Scanning forging tools using the 3D scanner (ROMER Absolute ARM 7520si integrated with the scanner RS3 (Hexagon Manufacturing Intelligence, Aarau, Switzerland) together with the Polyworks software 2015);
- A thorough analysis of selected forging processes, in particular the working conditions of tools using a high-speed (Casio Exilim Pro EX-F1, Casio, Tokyo, Japan);
- CATIA software (V5R20 program by Dassault, Vélizy-Villacoublay, FRANCE) for designing and supporting engineering works;
- Development of simulation of robot motion and trajectories of RobotStudio (ABB, Warsaw, Poland) manipulators;
- Labview software (National Instruments Corporation, Austin, TX, USA) for developing a control and measurement application for lubricating and cooling systems;
- Other classical measurement and research methods.

3. Own Studies

The authors of this article have conducted many studies and tests related to the influence of tribological conditions on the wear of forging tools, which includes the following publications in this field [2,55,67,68]. We can reach conclusions about the significance of lubrication on changes in tool temperature based on the presented exemplary course of die temperature during a forging process (Figure 2).

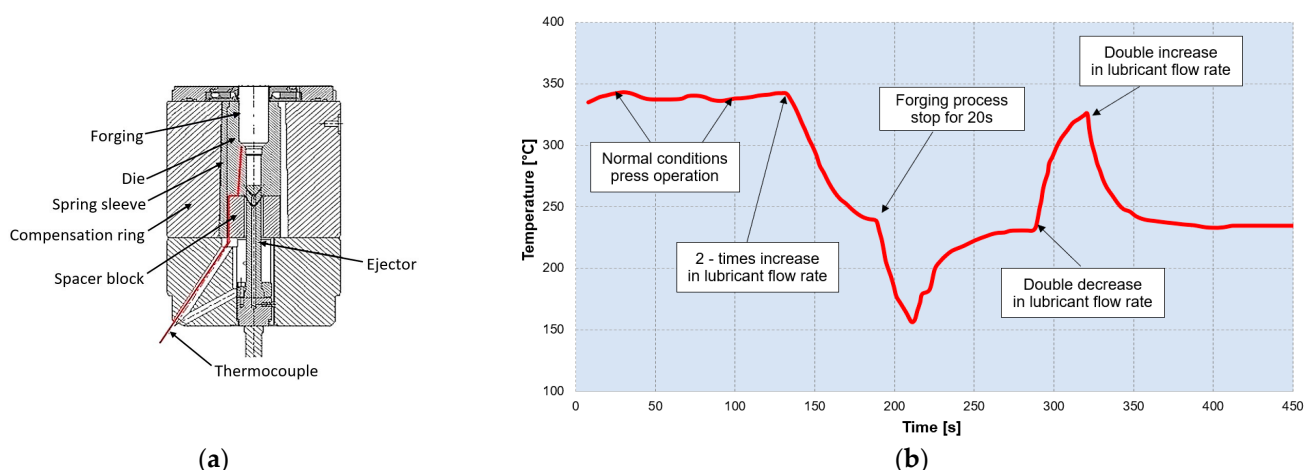


Figure 2. Own research: (a) a scheme of the thermo-couple mounted into the tool set and (b) a view of the temperature distribution and changes of the die during forging with the indicated disturbances in the process.

To that end, a proprietary measuring system was built, which enabled a continuous temperature measurement using a thermocouple inserted into the matrix through a special hole (Figure 2a). The tests showed (Figure 2b) that a double increase in the dose of lubricant caused a decrease in the tool temperature by more than 100 °C. In turn, stopping the press for 20 s caused a rapid further decrease in the tool's temperature. Another start of the forging process caused a temperature increase, and a subsequent two-fold reduction of the lubricant supply raised the tool temperature again. Thus, in the analysis of the total course of the temperature changes, depending on the changes of the tribological conditions implicated by the increase/decrease in the lubricant dose, we can observe the importance of a proper and controlled lubrication for the whole wear of the tool. An analogous situation referring to the changes in the tribological conditions caused by lubrication on the tool wear is shown in Figure 3. In the presented photographs from the thermovision camera, we can observe dynamic temperature changes on the surface of the analyzed tools as a result of lubrication. The analysis of a sequence of 7 s of the process demonstrated that at

14 s (of the lubrication still lasting for about 2 s), the temperature on the tool surface in a selected point equaled 95 °C (Figure 3a) then rapidly increased after the following 3 s by over 100 °C to about 207 °C (Figure 3b).

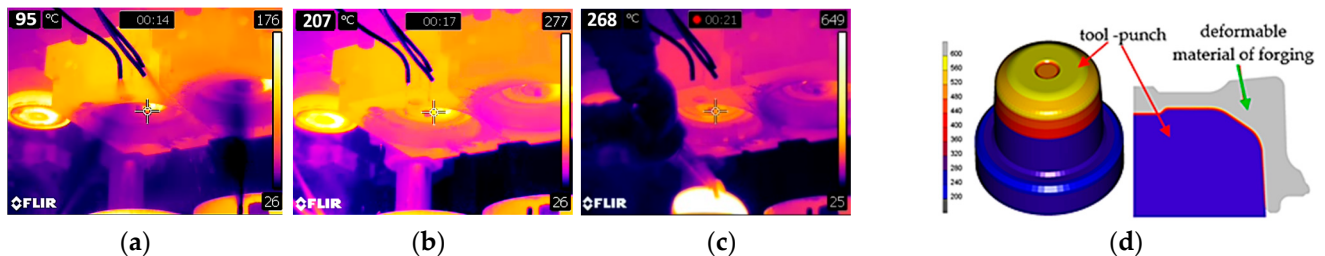


Figure 3. Results of thermal camera recorded during a cycle of 7 s with the temperature distributions on the tool-punch in the process of making a disk forging: (a) the cycle of tool lubrication—the temperature in the marked point equals 95 °C, (b) 3 s after the lubrication—the temperature goes up about 100 °C, (c) just 1 s of the end of the forging process, and (d) the field of temperature distribution on the analyzed tool during forging obtained from FE modelling [55].

After the deformation process—another 4 s—as a result of the change of the deformation work into heat, the tool surface temperature increased by 60 °C (Figure 4c). The additional tests performed with the use of numerical simulations showed that, at the moment of contact of the forged material with the punch, the temperature increased by over 560 °C (Figure 3d). This proves how rapid and large temperature changes take place in forging processes, which makes the forging tools heavily loaded thermally and mechanically, and this significantly affects their wear. For this reason, any changes, even minimal ones, of the settings or the cooling–lubricating expenditure, can bring about deciding and irreversible changes, causing damage to the forging tools.

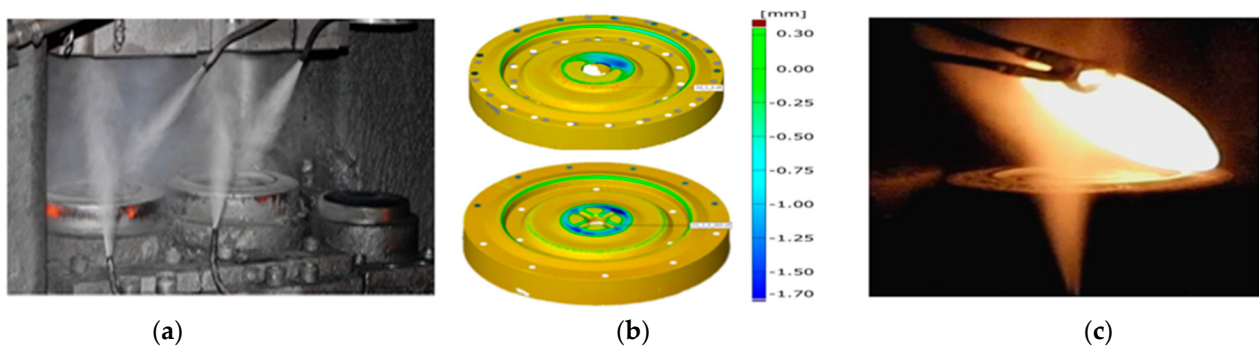


Figure 4. Semi-automatic manner of lubricant supply: (a) a photograph of the process during lubrication, (b) tool wear in the case of non-uniform lubrication (upper) and uniform lubrication (lower), and (c) poor synchronization of the lubricating systems.

Figure 4 presents an image of a semi-automatic lubrication technique realized on crank presses by way of manually setting the lubrication nozzles based on the operator's experience and knowledge. In this case, the direction of the lubricant supply depends on the position of the nozzles set by the operator. Excessive lubrication (Figure 4a) can cause disadvantageous properties of the forging and premature wear of the tools as a result of thermal shocks. Similarly, a lack of sufficient control of the lubrication process and an improper position of the nozzles in the process can be the cause of non-uniform wear (Figure 4b), which intensifies the areas exposed to abrasive wear and thermo-mechanical fatigue and significantly shortens the performance time of the tools as well as lowers the quality of the forging.

Additionally, a lack of synchronization of the lubricant exposition with the work of the forging aggregate and/or moving the forging to the next impressions (Figure 4c) can

negatively affect the tool durability (lack of sufficient lubrication) but also cause forging defects (improper microstructure after forging as a result of cooling).

In turn, in the case of a fully automated lubrication system, such as in a multi-operation process of forging a constant velocity joint (CVJB) performed on a transfer press [5], problems may occur as well (Figure 5).

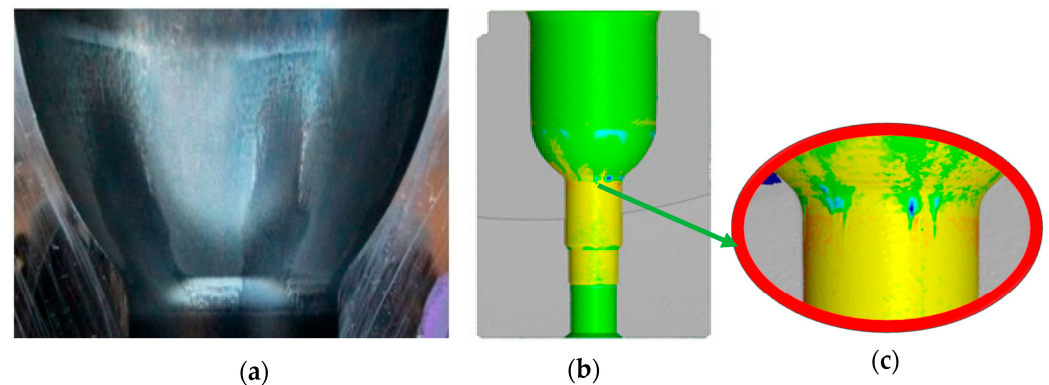


Figure 5. A non-uniformly worn tool surface: (a) a digital picture, (b) the scanning results, and (c) magnitude of indicated area—reduction of die cross-section.

The lubrication of dies in this process is realized by means of a specially constructed ejector that has openings with nozzles located at the end. Using a set of eight nozzles spaced evenly at 45° intervals, lubricant is supplied as the forging is pushed out of the die in the upper position of the ejector. The surface of the working impression of the tool is covered with a layer of lubricant with high intensity, depending on the distance of the given nozzle from the surface. In effect, there are areas where over-lubrication takes place as well as areas only minimally covered by the lubricant. This causes a non-uniform distribution of the lubricating agent, leaving clear traces on the die circumference and causing higher wear (as a result of adhesion) in the areas with excessive lubrication (Figure 5a). At the die surface, we can observe a difference between the yellow zones (Figure 5b) and the dark green zones reached by a smaller amount of lubricant.

In the case of the lowest areas of the tool impressions and improper tribological conditions (too low a tool temperature after lubrication), liquid from the grease may not evaporate, and it will remain. This causes an increase in the pressure value as a result of the appearance of an air pocket or a lubricant residue in this area (Figure 6a), which accelerates the formation of microcracks and the so-called Rebbinder effect (Figure 6b) and causes a forging defect in the form of an underfill (Figure 6c). Such a problem has often been observed in industrial forging processes.

A potential solution to the presented problem is improvement of the tribological conditions or elimination of the human factor for the sake of the application of more precise automated cooling–lubricating systems.

Investigations were also performed [36] referring to the determination of the tool lubrication manner with the use of a lubricating board equipped with a set of openings with different diameters and angles through which the cooling–lubricating agent was being fed (Figure 7).

The openings in the board were divided into two main sections. The first section had openings with the diameter of 3 mm and a spraying angle of 4° , which ensured a complete covering of the deepest and largest areas of the working impression (Figure 7a). In turn, Figure 6b shows a solution consisting of lubrication of the so-called die bridge, which is the key area of the tool due to the intensive flow of the material into the flash, which favors intensive abrasive wear of this area, hence the required precise lubrication and the use of openings with the diameter of 2 mm and the angle of 3° in the second section. Figure 7c presents an optimal solution of a simultaneous operation of both sections in such a way that the openings in Section 1 are replaced by the openings in Section 2, which cover the areas

of operation of Section 1. This makes it possible to precisely spray the impression with the bridge without “over-lubrication” of the remaining part of the tool, which is not working abrasively. Of course, it is necessary to perform further tests under industrial conditions.

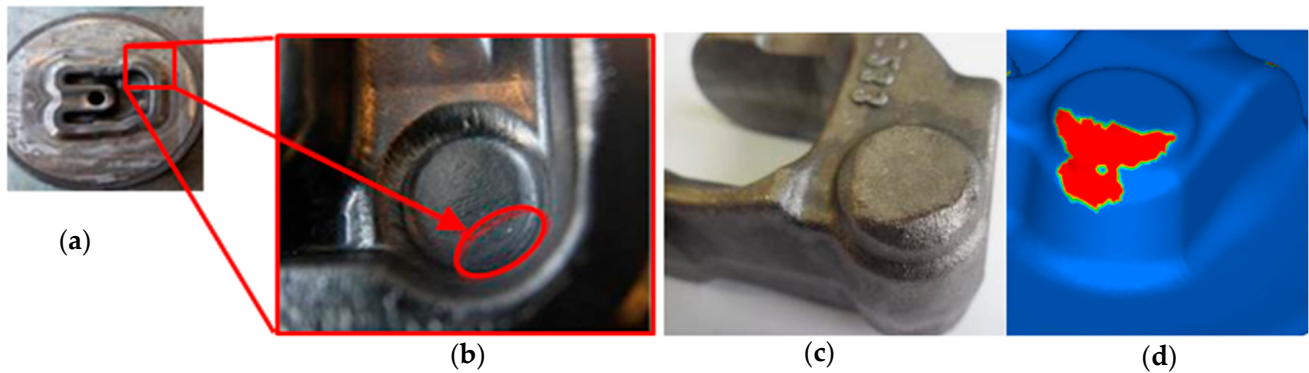


Figure 6. Cracking of the die inserts in the lowest area of the working impression caused by the remaining lubricant residue: (a) the die inserts with indicated area of accruing defects, (b) a magnification of the cavity image of the formed cracks, (c) an underfill of the forging as a result of “closed” volumes of grease or air, and (d) the results of numerical modelling with the use of the “trap” function (red color means unfilled).

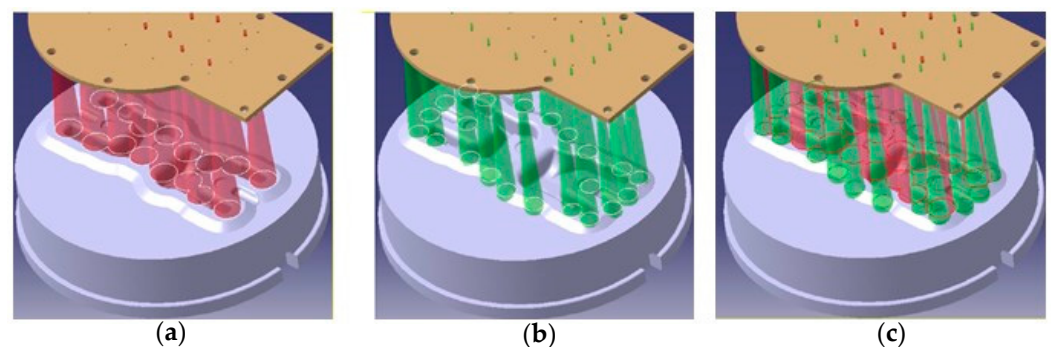


Figure 7. Modelling of the direction and size of the lubricant dose: (a) the work of the first section, (b) the second section, and (c) the optimal solution.

4. The Proprietary Concept of a Lubrication and Cooling System

Based on the conducted investigations in the area of lubrication and analysis of the tribological conditions in die forging processes, the authors elaborated several cooling–lubricating systems dedicated to processes of producing forgings [30] because, as has been demonstrated, ensuring the optimal forging tool lubrication has a significant effect on the durability of the tools and the quality of the forgings. In the usually applied manual and semi-automatic lubricating devices, the operators (based on their extensive professional experience), by means of a valve, “subjectively” regulated the dose of the lubricant and the time of its exposition through the lubricating nozzle by pressing the pedal with a foot. This caused a lack of stability of both the lubrication and the tribological conditions of the forging process. For this reason, the authors developed and constructed a new cooling–lubricating device, which makes it possible to control and precisely set the most important work parameters of such a system, which is simultaneously cooperating with the forging aggregate (Figure 8).



Figure 8. A dosing–lubricating device enabling regulation of cooling–lubricating agent expenditure: (a) a view before forging process and (b) a view 1 s after finishing forging—automatic start of lubrication.

Compared to the first versions, the present lubrication systems are standardized and constructed modularly, which, with a little modernization, enables a fast and repeatable construction of such devices dedicated to a specific forged item—a forging. Die forges, being the main recipient of such systems, are satisfied with the high efficiency and interested in a further expansion and modernization of such devices for other die forging processes. Special attention was paid to the working cycle of the device (sequence order): the blow-through cleaning the scale, the cleaning and lubricating, and a precise and repeatable lubricant dose with a possibility to differentiate the proportions for the subsequent nozzles and setting the sequence of the blow-through and the lubricant application. To that end, a proprietary peristaltic pump with a stepper motor was used, which makes it possible to precisely “mechanically” measure and dose the lubricant as well as push, through a special nozzle and elastic conduits, compressed air supplied by the installation with the pressure of 4–8 bars. All the settings are realized by the operator by means of an easy-to-use HMI (Human Machine Interface) panel. The appropriately selected time-dose sequences referring to lubricant ejection favour proper liquid spraying, hindering the formation of graphite in the lowest areas of the working impression and the remaining of water on their surface. The developed device is equipped with an anti-sedimentation mixer, which ensures uniformity of the graphite suspension in water. Additionally, the system has an automatic cleaning function, which maintains constant lubrication parameters. Figure 9 shows an exemplary diagram of a tool’s working cycle.

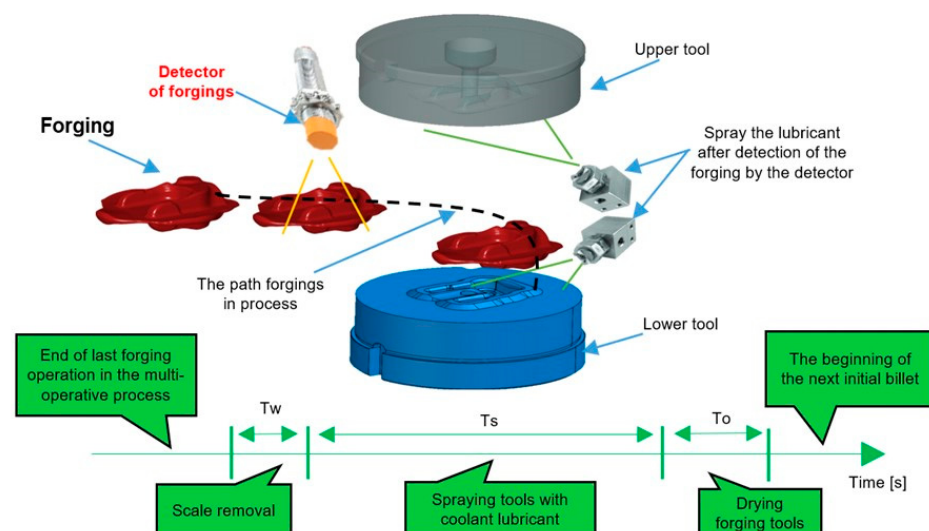


Figure 9. An exemplary work cycle diagram of developed cooling–lubricating system.

The performed studies and tests demonstrated that the elaborated system worked very well under industrial conditions in the two selected forging processes: a yoke forging and a spur wheel forging. Figure 10 shows exemplary comparative results referring to 3D scanning of the upper dies used in the roughing operation for a yoke forging, which worked with the use of the developed as well as the old (used so far) lubrication system [55].

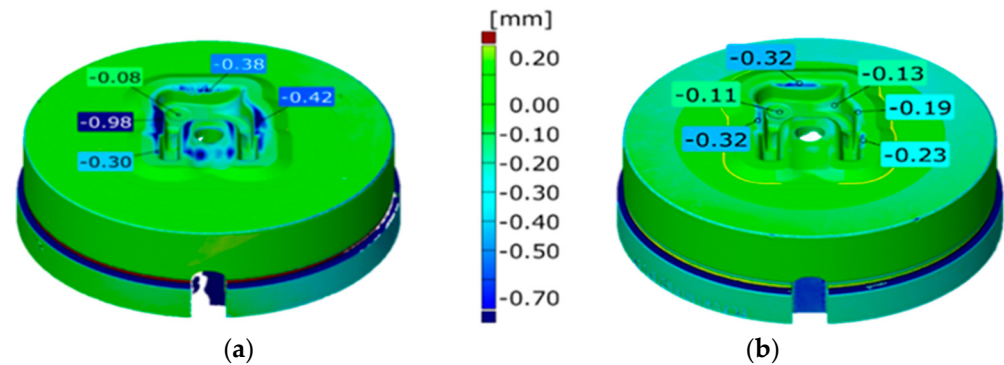


Figure 10. The 3D scanning results for: (a) an insert after 9000 with the old lubrication system and (b) an insert after 16,000 with the new lubrication system.

The presented exemplary comparative results point to the fact that ensuring “better” tribological conditions through the application of the elaborated lubrication system caused an almost two-fold increase in durability. The wear areas were larger and present mainly in the vicinity of the formation of the forging’s “shank”, whereas in the case of the new lubrication system, the wear was localized only in the rear part of the forging. For this reason, further works and tests require modification of the lubrication direction settings.

The developed cooling–lubricating system was also applied in another forging process—hot die forging of a spur wheel forging. The mean durability of the dies used in this process, by means of the old semi-automatic lubricating device, equaled about 7000–8000 forgings; after this number of forgings, due to loss of dimensions on the radius of the flash material’s exit, the tools were removed from further production. The global results obtained from the 3D scanning of the lower die inserts used in the roughing operation after an increasing number of forgings are presented in Figure 11.

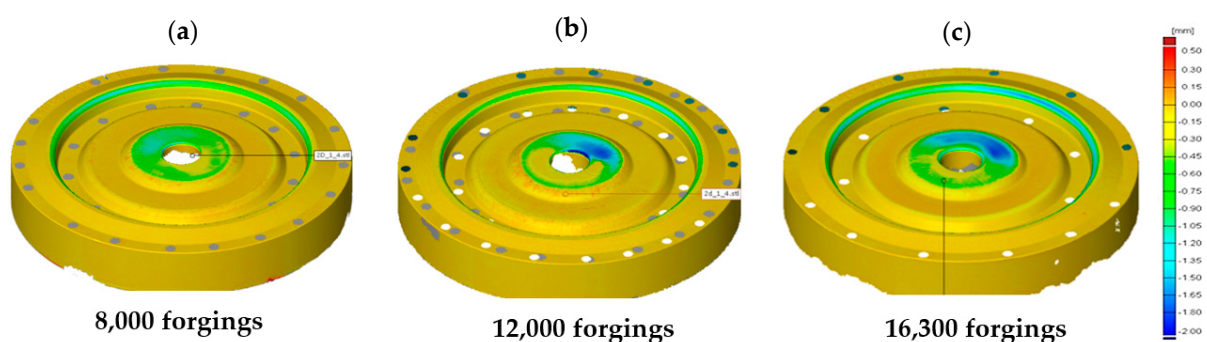


Figure 11. The 3D scanning results for the lower tools used to forge a spur wheel with the use of the elaborated lubrication system: (a) a die after producing 8000 forgings, (b) 12,000 forgings, and (c) inserts after 16,300 forgings.

By analyzing the results obtained in the form of scans of the worn tools after different numbers of produced forgings, in the aspect of the effect of the new lubrication system, we can conclude that the introduction of the developed process solution ensures more stable tribological conditions, which causes a reduction in material wear, especially in the final period of the tool’s work. The presented investigation and test results conducted by means of the constructed cooling–lubricating system provide inclinations to conduct further, more

advanced studies referring to both the optimization of the lubricant dose and the direction of its feeding and frequency as well as some additional parameters connected with the lubrication process. Future studies should also develop more dedicated cooling–lubricating systems.

Direction of Further Research

Currently, research is underway to develop further solutions that focus on automated lubrication systems that work with manipulators in robotic forging cells. Figure 12 presents the results of research related to the development of a lubrication and descaling system with the use of a device that, right after forging, enters between the forging tools and simultaneously blows the upper and lower tools and then lubricates them.

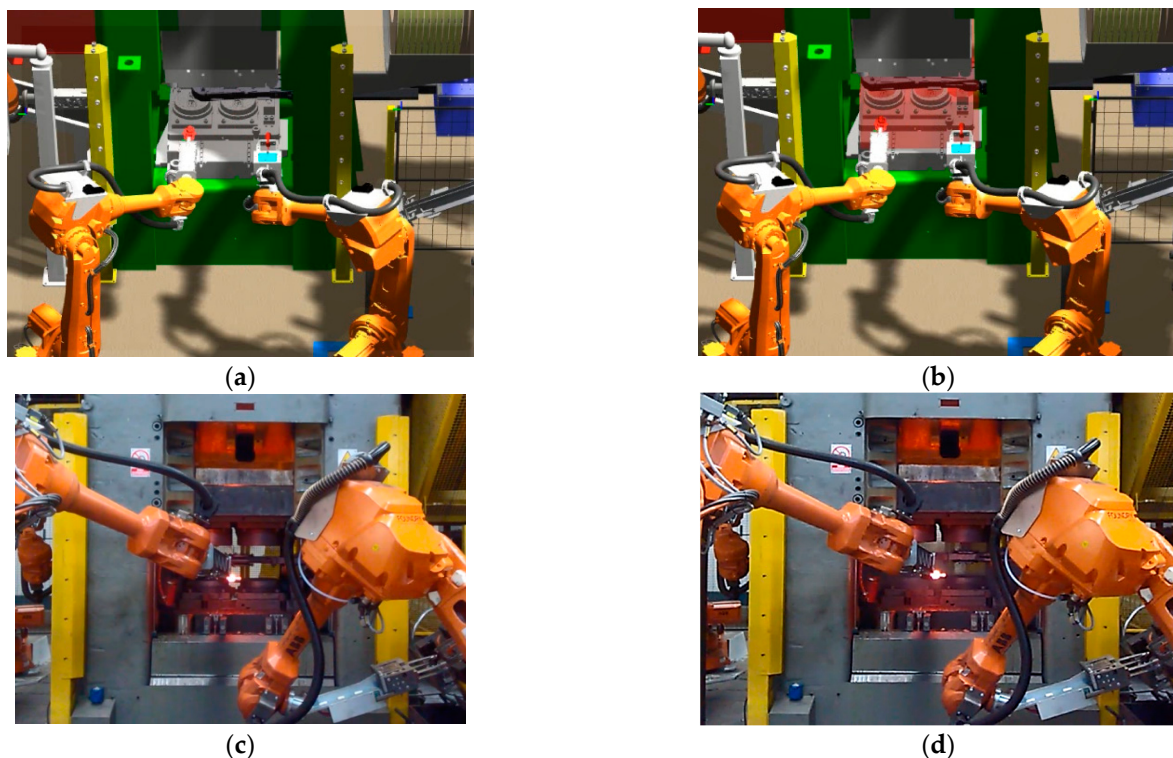


Figure 12. Robotic production cell on a crank press with developed automated cooling–lubrication system: (a) results of simulation by Robot Studio software—before lubrication, (b) during lubrication—simulation, (c) before lubrication—industrial process, and (d) during the cooling and lubricating process by means of an automatically driven lubricating plate—industrial condition.

In this case, the production cycle is 16 s, and the forging process concerns the production of a forked fork in a double system in three operations. After the forgings are completed, a special lubricating plate enters through the press window from the right side, which within 2.5 s performs the entire lubrication process (blowing and removing scale and applying the lubricant). Although during 2 months of operation of such a production cell, the tool life was doubled and the lubricant consumption was reduced almost as much, both the developed lubricating device and the entire forging process are still being optimized.

5. Summary and Conclusions

The study presented a review and analysis of the effect of the application of different cooling–lubricating agents, lubrication techniques, and cooling–lubricating devices used in die forging at elevated temperatures. The performed analysis demonstrated that, presently, the most commonly used lubricants in die forging processes at elevated temperatures are lubricants based on graphite with modified properties dedicated to a specific forging process. We also observed that, currently, great emphasis is placed on the development

of cooling and lubricating devices, as they can provide stable and repeatable conditions as opposed to the still popular manual lubrication, which is affected by the subjective human factor. The performed review of the state of the problem has proved that both the selection of the lubricant and its volume and manner of application on the tools constitutes an ongoing and unsolved problem, where the most important issue is the optimal lubricant dose and its feeding technique, which has been confirmed in the authors' own tests. The performed examinations have demonstrated that, despite die forging processes at elevated temperatures being similar to each other, each of them is a little different, due to, e.g., different shapes of the tools, the preform, the slug forging, the temperature field distribution and the production cycle, and slightly different tribological conditions resulting from applying different concentrations of the same lubricant. Because of this, each process should be approached separately, and for each of them, both the lubricant and the other parameters of its exposition, including the lubrication manner and even the type of the lubricating device, should be individually selected. Based on the status of the issue, the following key conclusions were drawn.

- The cooling–lubricating system elaborated by the authors, presented in this work, makes it possible to examine the effect of the amount and frequency of the lubricant dose on the wear of the tool for the given process as well as to select and ensure the optimal tribological conditions in the process. For this reason, performing tests and investigations in this area (such as complex and long-term analyses of a given forging process) is fully justified not only scientifically but also financially;
- The obtained test results showed great possibilities for industrial applications of such systems in different die forging processes, both in the case of a yoke-type forging and spur wheel forging. The durability of forging tools, in the case of using the developed lubrication system, was increased by two times;
- Further studies are also planned, which will be connected with further expansion of the developed lubrication parameters as well as selection of the optimal lubricant temperature with respect to thermal fatigue and the optimized procedures of automatic cleaning of the cooling–lubrication system after the forging process;
- Next, we plan to automate these systems for forging processes and for hammer forging processes.

Author Contributions: Conceptualization, M.H. and Ł.D.; methodology, M.H.; software, M.R.; validation, J.M., R.T. and M.R.; formal analysis, M.H. and Ł.D.; investigation, J.M. and R.T.; resources, M.R.; data curation, Ł.D. and J.M.; writing—original draft preparation, M.H. and M.R.; writing—review and editing, M.H. and J.M.; visualization, J.M. and R.T.; supervision, M.H.; project administration, M.R.; funding acquisition, R.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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