POSSIBILITIES OF ENSURING A STABLE AND OPTIMAL OPERATING TEMPERATURE OF FORGING TOOLS USING AN INDUCTION HEATING SYSTEM WITH THE POSSIBILITY OF TEMPERATURE CONTROL AND RECORDING

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Abstract

The article determinates the operating temperature of forging tools intended for the hot precision forging process of a selected series of die forgings, with respect to the operational durability of the forging equipment. The durability of forging tools is one of the important aspects affecting the price of the final product in the form of a forging, especially in the case of a small forging, up to 45 %. The optimal operating temperature of forging tools is usually selected for a given technology, but also based on the heat balance resulting from the heat generated because of plastic deformation and friction of the forging as well as the heat released by the tools during their cooling and lubrication. Only a proper selection and maintenance of temperature ensures high durability. As part of the research work, a permanent system for measuring and recording the temperature of forging tools in a die forging process on a hammer, with ongoing temperature registration for the whole set of tools, was presented. Various methods of heating and reheating forging tools dedicated to hot drop forging processes were presented and analyzed, including heating using natural gas as a medium and induction heating using a developed system based on two 2 x 10kW inductors. The obtained results indicate that the appropriate control of the tools temperature and their induction heating/reheating gives the best results in terms of minimizing the energy consumption necessary to ensure the stability of the tool operating temperature conditions.

Keywords: Precision forging on hammer, forging dies, heating of tools, induction heating system

1. INTRODUCTION

Forging dies used in forging processes at elevated temperatures are exposed to the operation of many factors, which include cyclic changeable mechanical and thermal loads, causing mainly thermo-mechanical wear of the tools, as well as intensive friction during deformation, revealing itself in the form of abrasive wear. This means, in hot drop forging processes, many other destructive mechanisms are present as well, such as: plastic deformation, oxidation, adhesive wear, fatigue cracking, etc. Additionally, during the contact of the hot material of the formed forging with the tool, we can observe overheating or cracking because of non-uniform accelerated heating of the tool material as well as too intensive cooling during lubrication after forging. Problems of this type are eliminated by way of maintaining the proper tribological conditions, that is preheating the tools before the forging to their working temperature and ensuring cooling during lubrication to avoid non-uniform heating and its accompanying stresses [1]. According to the technology of hot drop forging, confirmed e.g. by the study [2], to avoid premature tool wear and other damages, and with the purpose to ensure the optimal temperature conditions, the dies should be heated to 100-200 ºC. In another study [3], the authors, based on their investigations, point to the working temperature of the tools used to forge steel forgings in the scope of 205-260ºC. In turn papers [4, 5], we can find only guidelines about how heating helps avoid damage. We should also consider the work of the forging tools throughout a longer period and take into consideration the thermal balance connected with the heat generation during the formation of the deformed forging material (because of a change of the plastic deformation work into heat) as well as the heat because of friction. Such a balance depends largely on the volume/mass of the tool and the charge material, and their inappropriate selection can cause overheating or cooling of the tool during the production cycle, which, in consequence, can lead to premature wear. For this reason, it is important, especially in the aspect of tool durability, to both provide proper heating before the forging process and maintain stable tribological conditions ensuring a thermal balance in the forging process as well as a continuous temperature control. At present, the preheating of the tools usually takes place after they are mounted in the forging aggregate or directly before their mounting (in resistance furnaces) and the beginning of the forging process. The commonly applied heating methods include heating the tool surfaces through contact with a heated waste material (often applied, **Figure 1a**), heating the already mounted tools with gas burners (**Figure 1b**), heating the dies on burners located separately in the aggregate's vicinity (this refers mainly to dies with a large thermal capacity), heating the tools by means of electric heating mats (rarely applied, **Figure 1c**), or heating the tool surfaces with infrared radiators on a press/hammer or inside a furnace (technology developed at some forges) [6]. Some forges apply also a method of heating the tools with infrared lamps on a press/hammer or inside a furnace (**Figure 1c**) [7]. This means, these are not universal methods and are often ineffective. Sometimes, also, no preheating is applied – the tools are then covered with special separating substances (**Figure 1d**) [8]. Each of the mentioned methods has its pros and cons, and the method selection is dictated by availability, experience and price related to efficiency.

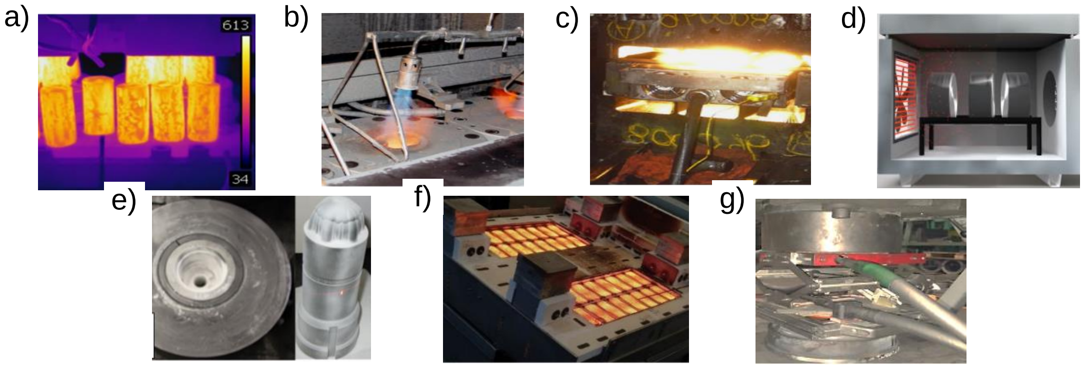

Figure 1 Presently applied forging tool heating methods a) a waste/charge material, b) gas burners, c) heating mats, d) infrared radiators, e) no heating – application of welding foam, f) technology of a flameless gas burner, g) inductors

For example, heating with a waste material is the simplest yet low efficient method as the average heating time is about 0.5-1h, and additionally, the long contact of the hot material can negatively affect the surface layer of the tool. We can also encounter a method of preheating carried out mainly with the use of thermal oil electrically heated and conducted through channels in a die. In the available literature, there are many publications referring to the analysis and application of different methods of heating/reheating of forging tools [9]. A few patents [10, 11] protect some specific solutions of initial preheating or heating of forging tools. This said, we should clearly emphasize that recently, especially induction heating has been intensively developed as it ensures high efficiency and rate of heating as well as provides the possibility of additional heating of the forging tools. Apart from the selection of the proper method of heating the tools, a key aspect is also the temperature control before and during the forging process, especially a correct and continuous measurement of the tool temperature. It seems that the most convenient technique is temperature control with the use of thermovision, owing to the possibility of analyzing a larger area spectrum as well as performing a measurement at a distance from the hot objects and of visual archiving of results. However, at the same time, it is a relatively expensive method because of the non-contact type of measurement. Another way providing high precision is a contact measurement with the use of thermocouples, yet it is often troublesome, due to the thermocouples being mounted in the tools. It should also consider the unavoidable confounding factors resulting from the non-contact temperature measurement [12].

The aim of the study is a measurement and analysis of the temperature of forging dies used to produce precision forgings on hydraulic hammers during both heating and reheating and, on this basis, a development of an effective way of heating/reheating of the tools together with a system of temperature control, which is to ensure increased operational durability of the tools.

2. TESTS AND DISCUSSION OF RESULTS

The planned investigations were divided into four stages: 1. Measurements of the forging tool temperature and their analysis with the use of a thermo-vision camera (non-contact measurements). 2. Measurements of the forging tool temperature by means of thermocouples (contact measurements). 3. Analysis of the temperature distributions in the dies with the use of numerical modelling. 4. Development of a heating and temperature control system.

2.1. Measurements of the forging tool temperature and their analysis with the use of a thermovision camera (non-contact measurements)

The first and fundamental stage of the realized tests were measurements of the forging tool temperature distribution by means of a thermovision camera. The forging tools, prepared beforehand, were mounted on a hydraulic hammer and then heated with the use of gas burners (**Figure 1b**). The heating system using gas burners has low effectiveness and does not allow for a proper heating of the upper and lower forging tool. To achieve the maximal temperature, it is necessary to heat them to the temperature within the scope from 1 h to 1:15 h. Below, we can see the thermograms with the temperature distributions, both for the lower and upper forging tool prepared by means of a thermovision camera FlirT840 (**Figure 2**).

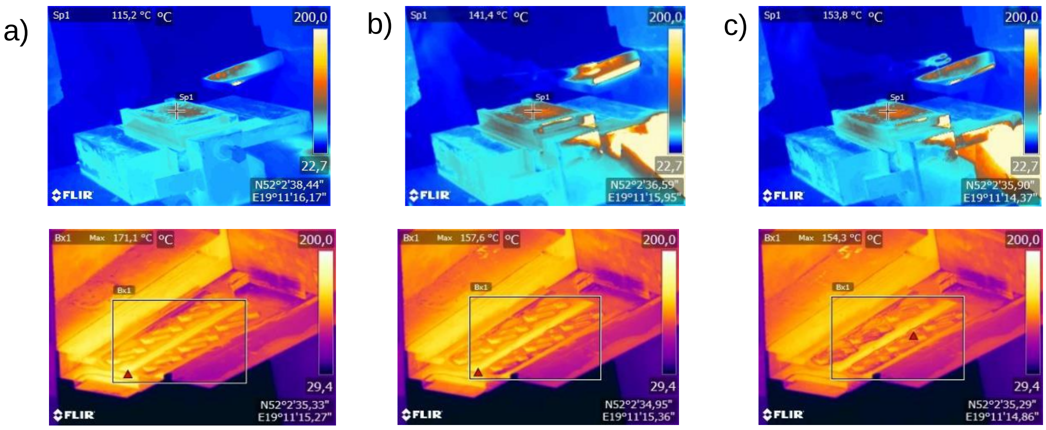

Figure 2 Temperature distribution of the forging tools before the hammer activation for lower and upper dies: a) beginning of production cycle, b) middle of cycle, c) end of cycle

During the realization of the measurements, we can notice that the temperature of the forging tools is unstable and changeable. The forging tool temperature changes also during the forging process. It is much higher before the beginning of the forging process for the upper forging tool than in the case of the lower forging tool. During the forging process, due to a longer contact of the hot charge material with the lower forging tool, it increases because of the heat emission from the charge material to the forging tool. In the case of a temperature drop of the upper forging tool below 100 °C, the process is interrupted, and the tools are additionally heated. Such a cycle process equals about 40 minutes of the forging process and 20 minutes of heating the tools with gas burners. Based on the presented thermograms, we can observe that the difference between the temperature of the lower and upper tool decreases together with every next produced forging. From the middle of the cycle, the temperature of both tools stabilizes, and the temperature distribution becomes more uniform. Also, undoubtedly, the type of the lubricant as well as the intensity of its application and blow-through of the forging tools affect their condition and thus also the temperature and stability of the process.

2.2. Measurements of the forging tools with the use of thermocouples (contact measurements)

The following stage of the conducted studies were temperature measurements of the forging tools by means of K-type thermocouples. The aim of the tests was to record the tool temperature and determine the heating and cooling rate at specific moments of the forging hammer's operation. To that end, two forging tools were prepared beforehand, an upper and lower one, with proper holes for the thermocouples. The holes were made in distance of 5 mm from the working surface. Each forging tool had two holes, one for a temperature measurement under the roughing cavity, and one – under the finishing cavity. **Figure 3** shows the measurement results from a few production cycles, consisting of heating the forging tools for the forging process, a process of die forging on a hammer, additional heating of the forging tools, a process of die forging on a hammer, additional heating of the forging tools, etc., and cooling to ambient temperature at the end.

a)

b)

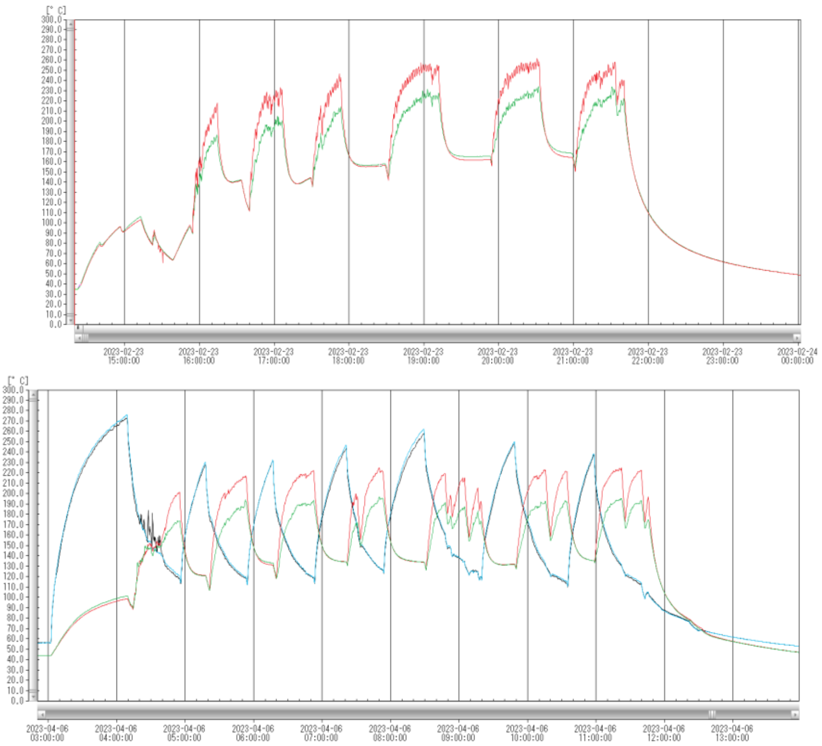

Figure 3 Results of temperature measurements for a) upper and b) lower forging tools with the use of thermocouples (red – roughing cavity, lower tool; green – finishing cavity, lower tool; blue – roughing cavity, upper tool; black – finishing cavity, upper tool)

The temperature of the lower forging tool stabilizes during the forging process. The lower tool reaches a temperature of 220-225 °C in the roughing cavity and about 190-195 °C in the finishing cavity.

a)

b)

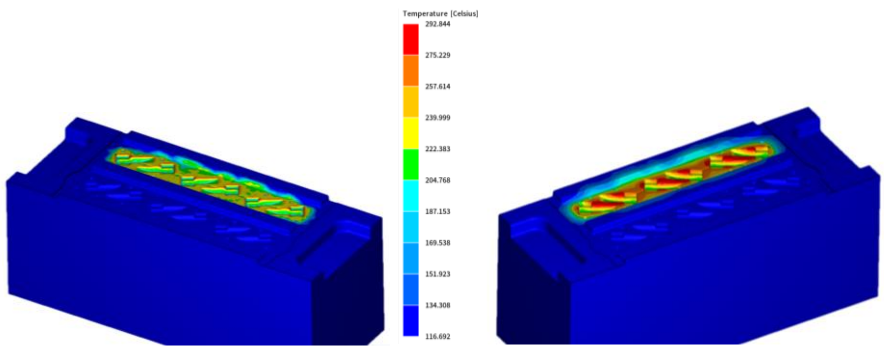

Figure 4 FEM results – temperature distribution in 250 cycle (2 s after forging): a) upper die, b) lower die

2.2. Analysis of the temperature distributions for tools with the use of numerical simulations

Numerical simulations for the analyzed tools used in the forging process were carried out by means of FORGE NxT 3.0. The initial-boundary conditions referring to the formation and the initial temperature of the charge material, the tool temperature and the processes were assumed based on the operation sheets. The assumed ambient temperature equaled 50 °C, the charge temperature 1250 °C, the tool temperature 200 °C, the thermal conductivity coefficient in contact is 10 kW/m²K and the thermal conductivity coefficient with the environment 15 W/m²K; the expansion coefficient is $12 \cdot 10^{-6}$ K^{-1}; the cooling between the operations is 3 s; the lubricant is water with graphite. **Figure 4** shows the results with the temperature field distributions for both dies in steady state (250 forging cycle, 2 s after forging). Analyzing the results of the temperature distribution in the 250th cycle (**Figure 4**), it can be observed that the upper tool is cooler by about 50 °C compared to the lower one. It should be clearly emphasized that when analyzing the results of temperature distributions in FEM (**Figure 4**), they do not confirm the measurements made in industrial conditions with the use of either thermocouples or thermovision. On this basis, we can conclude that the issue of temperature conditions for the dies is much more complex as, under real conditions, the temperature of the upper tool begins to clearly decrease, whereas that of the lower tool slightly increases. For this reason, to ensure stable and repeatable thermal conditions, it is necessary to elaborate an effective system of heating and temperature control in the tools as it is crucial in the aspect of both the forging quality and the durability of the instrumentation.

3. ELABORATED SYSTEM OF EFFECTIVE HEATING/ADDITIONAL HEATING WITH A TEMPERATURE CONTROL SYSTEM

As a result of the performed studies, a decision was made to implement a system of fast heating and reheating of the forging tools. Due to a low thermal capacity of forging tools used to produce small size forgings (dimensions of the first tool are 150 mm x 150 mm x 400 mm, i.e. the mass of about 71 kg), in processes of this type, it is necessary not only to heat the forging tools at the start of the production but also to periodically reheat them. This, in consequence, causes process downtimes of 20 minutes. All system consists of two inductors with the power of 2·10 kW. Each inductor is controlled individually. This makes it possible to optimally select the power and time of the heating and, in consequence, also the rate of the forging tools' heating. Each inductor is equipped with thermocouples, which record the temperature in the contact with the forging tool's surface on an ongoing basis. This solution makes it possible to set the maximal temperature at which the system stops heating the forging tool. This helps avoid possible tempering in the case of its too rapid heating. The system allows selection of the heating time and the current for a given inductor. To verify the correctness of the induction heating system's operation, detailed tests were carried out during the forging of a precise element of a ring section type. After the end of the heating process, the induction heating system was removed from the processing area, which made it possible to record the image from the thermos-camera for the upper and lower tool (**Figure 5**) to determine the temperature distribution on the tools.

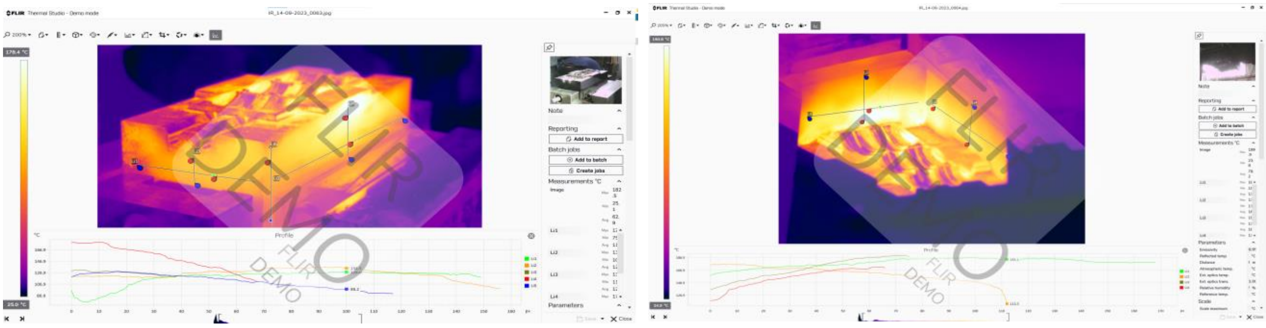

Figure 5 Analysis of the temperature distribution in the FLIR Thermal Studio application after the end of the heating process for a) the lower tool, b) the upper tool

Additionally, to perform a more thorough analysis of the tool, a decision was made to use the FLIR Thermal Studio package, which allows for a full analysis of the tool by way of marking the cross-sections and then observing the temperature difference on the diagrams. The conducted analysis makes it possible to notice that, in the case of the lower tool, the temperature changes from about 180 °C at the upper surface to as much as about 120 °C in the case of ⅓ height from the bottom, for the vertical cross-section of the side tool. In turn, in the case of the temperature analysis in the horizontal section, the visible temperature difference is much smaller and oscillates around 30 °C. A similar analysis for the upper forging tool makes it possible to notice that the temperature changes from about 170 °C at the upper surface to even 110 °C in the case of ⅓ height from the tool's bottom for the vertical section of the side tool. In turn, in the case of a temperature analysis in the horizontal section, the visible temperature difference is much smaller and oscillates around 30 °C. In the case of heating with the use of the system described above, the heating time of 20 minutes was achieved, with respect to gas heating of 1:15 h and reheating of 7 minutes. The system in question is efficient and can be used in industrial processes of die forging. It is also predestined to be used in the case of automatization of processes of die forging on hammers and presses.

4. CONCLUSION

The temperature measurements with the use of thermocouples are very accurate but also troublesome, due to their assembly in the tools and their possible damage during the work of the forging hammer (high vibration). The measurement by means of a thermos-vision camera seems to be more convenient as it is realized at a distance from the hot objects and it allows for the possibility of visual archiving of results, however, it is also burdened with error due to confounding factors. In the analysis of results, we can notice that, in the case of a process connected with optimization of the adjustable parameters, it is possible to shorten the time of heating and reheating of the forging tools with the use of an induction heating system.

The results of temperature distributions in FEM do not confirm the measurements made in industrial conditions with the use of either thermocouples or termovison, that the issue of temperature conditions for the dies is much more complex. The developed system of induction heating with a measurement and control of temperature is the most effective heating method, which makes it possible to reach the desired temperature already after 20 minutes. It can also be successfully applied for additional heating during process downtimes and breakdowns, in short heating cycles, in a short time of about 7 minutes.

The results of the measurements made by means of thermocouples and a thermos-vision camera agree. The elaborated system of heating/reheating of forging tools makes it possible to eliminate the problem of forging tools' tempering, owing to the installed thermocouples, which prevent the set maximal temperature value from being exceeded. The system is suitable to be implemented in industrial automatized and robotized processes of die forging. It allows for its easy and fast adaptation. The solution is universal and can be successfully applied for the implementation in both forging hammer and press aggregates.

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