Analysis of heat flow in the forging process

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Summary

This work presents some progress in a research project aimed at assessing the thermal field inside a finishing die during hot forging cycles, in the frame of a collaboration with a forging company.
The paper is focused on the procedure to evaluate thermal cycles at the surface and inside forging dies. The procedure consists of (i) experimental analyses at the industrial site during the production cycle, and (ii) numerical simulations developed at University.
Temperature vs. time curves from thermocouples embedded in the dies are compared with analogous from numerical simulations to estimate (i) the thermal field inside the die, and (ii) the maximum temperature on the inner surface of the die.

Key Words: forging tools, heat transfer, FEM, inverse analysis

1. Introduction

Inside forging dies thermal fields are difficult to study because, close to the inner surface, the heat flow change direction during the forging cycle. The workpiece heats the dies when they are in contact, otherwise dies are cooled by the environment and, above all, by lubricant. Among factors which determine the thermal cycle are (i) temperature of workpiece, (ii) sliding and/or deformation of workmaterial, (iii) production rate.
Numerical simulations can contribute to study thermal fields, but reliability of results depends, to a large extent, on the uncertainty in evaluating starting and boundary conditions; in addiction, thermal field is heavily influenced by parameters governing heat transfer and heat conduction which are usually unknown, due to difficulties associated to their measurement.
Research in this field is usually addressed to calculation of the heat transfer coefficient in lab experiments which partly resemble hot forging or rolling conditions dur-

ing the most critical phases of the working cycle, namely deformation of the work-piece and tool cooling by lubricant spray ([1] to [7]).

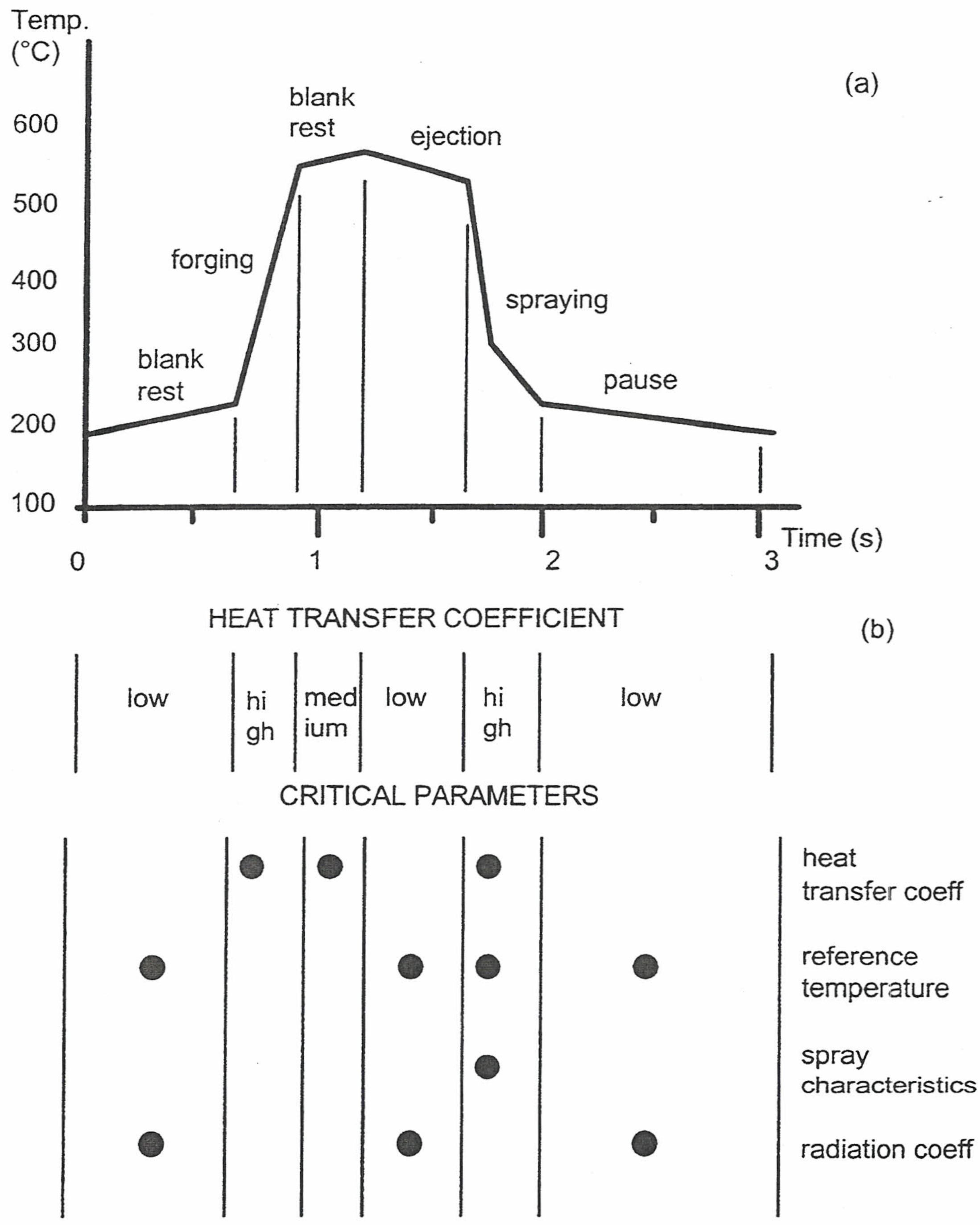

Fig. 1 - (a) temperature Vs time diagram for a generic surface point of a forging tool; (b) thermal parameters in a forging cycle

In this work a numerical simulation is developed to replicate mechanical and thermal effects in all phases of the finish forging for a chain roller for earth moving machines. Most critical values of the heat transfer coefficient used in the simulation, relevant to workpiece deformation and tool spraying are obtained, the former from lab tests [8], the latter from literature [7].
Six thermocouples are embedded in the lower dies to measure temperature during the forging cycle and to increase reliability of numerical results through inverse analysis.

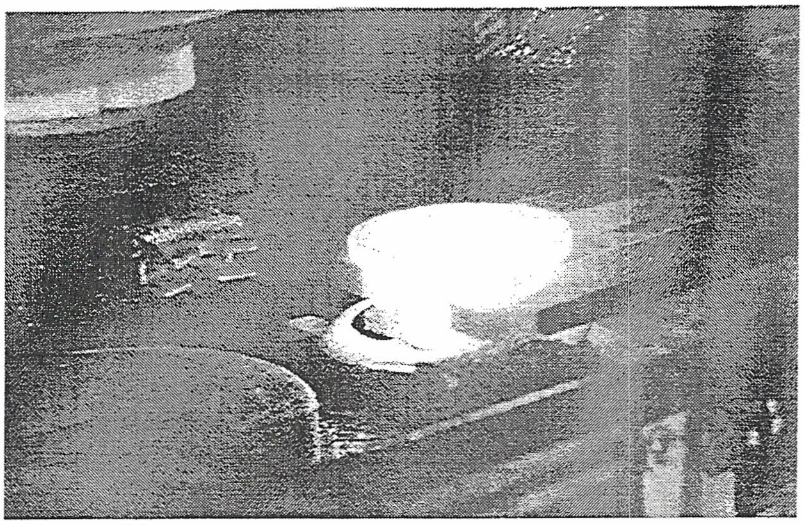

Fig. 2 - A roller leaving trimming station

2. Thermal analysis of phases in the hot forging cycle

A typical forging cycle can be divided into six phases (Fig. 1): blank rest (I), forging, blank rest (II), ejection, spraying and pause. For each phase, heat transfer between dies, on one side, and workpiece and/or environment, on the other, is worthy to be discussed.

Blank rest (I). The blank rests against the lower die before being deformed. Heat transfer between workpiece and dies is low because they are in contact only on a small portion of the surface. To calculate radiative heating or cooling of the die, it is necessary to estimate the radiation coefficient and the reference temperature, the latter being between room and workpiece temperature.
Forging. The workpiece is plastically deformed. Due to high contact pressure at interface, heat transfer rate is high. For this reason it is important a reliable estimation of an average value of the heat transfer coefficient.
Blank rest (II). After forging, the blank is in contact with dies for some whiles. The heat transfer coefficient is lower than in the previous phase because both temperature difference at interface and contact pressure are low.
Ejection. The workpiece is ejected from the die. Thermal characteristics of this phase are analogous to the first blank rest, but time interval is shorter, therefore in some analyses can be neglected.
Spraying. Dies are cooled by means of a lubricant spray. Depending on die geometry and on characteristics of nozzles, distribution of water over die surface is unequal, thus also the cooling effect. The diagram in Fig. 1 refers to spraying by means of an aqueous emulsion. Die cooling is extremely quick at the beginning, due to the very high heat of vaporisation of water. Afterwards, water vapour forms a steam layer which makes difficult estimation of the reference temperature; vapour temperature, 100°C, seems to be a good value. Also evaluation of the heat transfer

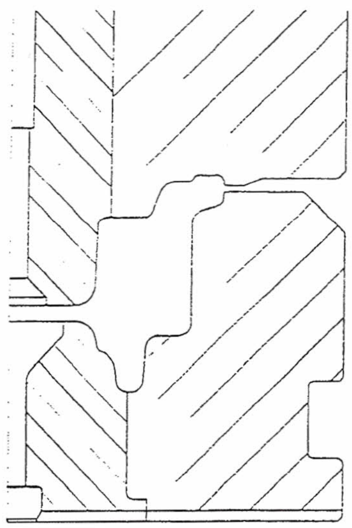

Fig. 3 - longitudinal section of the stage

coefficient is not easy, because different values should be used during and after vaporisation.

Pause. There is usually a pause before starting a new forging cycle. In this phase two effects contribute in changing the temperature of die surface. On one side, die surface cools towards environment, on the other it is heated by hotter areas of the die. Which one prevails of the two effects, is dependent on geometrical and operative parameters.

3. Numerical and Experimental Procedure in evaluating the Thermal Field

3.1 Steps of the Procedure

The forging sequence of rollers is made up of four steps: blocking, prefinishing, finishing and trimming. Fig. 2 shows a roller leaving the trimming station. In this work the thermal cycle is studied at the finishing station (Fig. 3), where tooling is subjected to heaviest thermo-mechanical conditions. Contact tooling is made up of four components, inner and outer lower die, inner and outer upper die. Activity is aimed at studying thermal field inside lower dies, which are more stressed and reach higher temperatures. Steps of the procedure are listed below:

- choice of thermocouples and of their position,
- development of the numerical simulation,
- measurement of temperature during the production run, and
- inverse analysis.

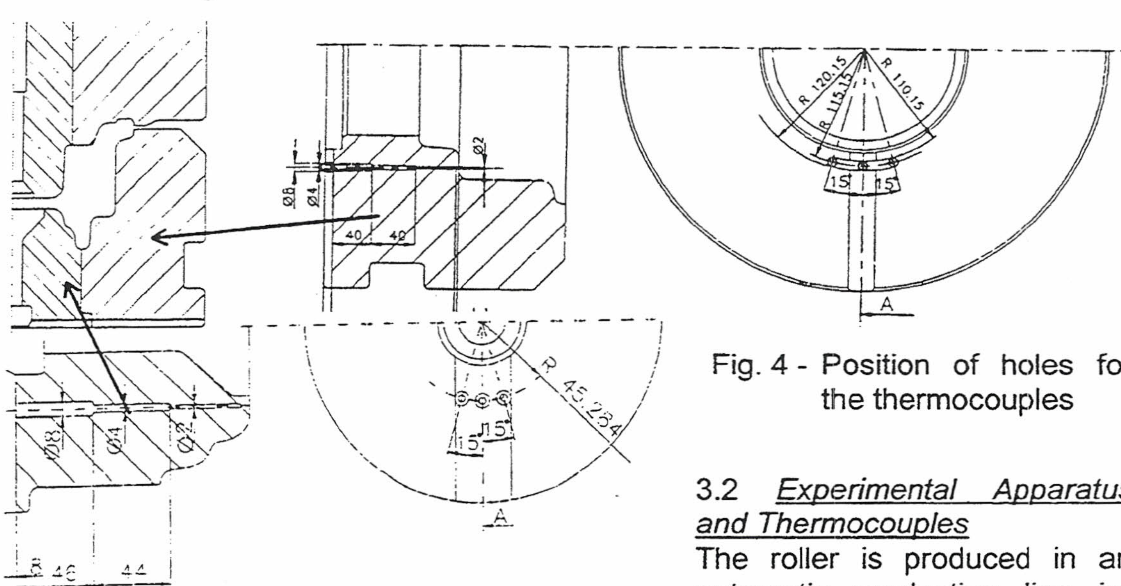

Fig. 4 - Position of holes for the thermocouples

3.2 Experimental Apparatus and Thermocouples

The roller is produced in an automatic production line including an inductive furnace and two Hasenclever multistage presses served by a robotized manipulator. Temperature is measured in the lower dies of the finishing station when thermal field is in a steady state, after two hours from the beginning of the run. Thermocouples in the same die are radially shifted of 15° from each other (Fig. 4), to reduce mutual disturbance. Sheath on thermocouples is necessary to be sure that the hot junction is at the end of wires. Wires must be as thin as possible to reduce the response time. Selected thermocouples are type K (chromel-alumel) and consist of a 1 mm Inconel sheath, MgO insulation and a grounded hot junction. They have a response time of about 0.18 s, comparable with deformation time (0.13 s). The choice of the diameter is based on the following reasons:

- dies are quite large, thermocouple wires are about 3 m long, therefore an adequate mechanical resistance is required,
- the selected dimension is the thinnest among those quickly available; thinner thermocouples require much higher delivery times and expenses.

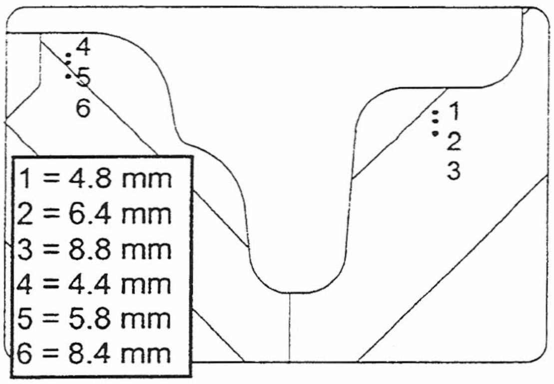

Fig. 5 - Distance of thermocouples from inner surface

Three thermocouples are in the inner die, three in the outer, as shown in Figg. 4 and 5. Inner die is mainly subjected to thermal fatigue, outer die is highly stressed. A minimum distance of 4.4 mm from the surface has proved to be adequate to maintain die integrity.

Thermocouples touch hole bottom and are kept in position by a special cement also used to fill holes. In its composition is steel (80% volume) and an epoxide resin (20%). Fig. 6 shows thermocouples out of dies before being cemented. Out of dies a Teflon sheath is used as an electric insulator.

3.3 *The Numerical Simulation*

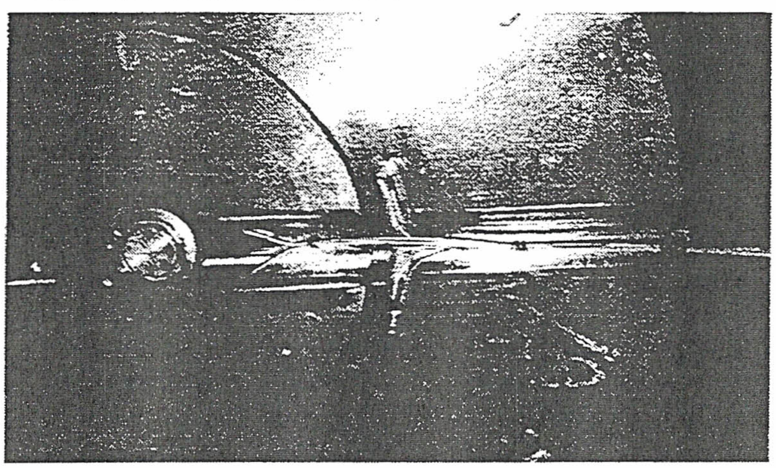

Fig. 6 - thermocouple wires out of dies

The numerical simulation is developed in two steps. A preliminary simulation is aimed at designing the experiment and, in particular, at identifying most appropriate locations for thermocouples on the basis of the following requirements: (i) proximity to highly stressed and hottest zones of dies, (ii) distance from inner surface adequate to maintain mechanical resistance of tools, (iii) accessibility. Dimension and position of holes are in Fig. 4, the distances from the horizontal surface are in the table of Fig. 5. Before starting the forging sequence, the blank is heated at 1250°. Workpiece temperature is about 1100°C at the entrance of the finishing station, measured using a pyrometer. Workpiece material is non-standard steel, tailored for the forging company. Tool material is an AISI H10 tempered at 400°C to have an hardness of 50 HRC.

True stress-true strain curves of both workpiece and die materials are inputted as piecewise curves from data obtained on a Gleeble testing machine.

A coupled thermo-mechanical simulation replicates the forging process, divided into four phases: spraying (Δt = 0.24 s), blank positioning (Δt = 0.72 s), plastic deformation (Δt = 0.13 s), ejection and pause (Δt = 3.91 s). It can be noted that there is not a complete correspondence between phases presented in Fig. 1 and the simulation, because some consecutive phases having similar thermal characteristic are analysed together.

Fig. 7 shows the simulation in the phase of blank positioning.

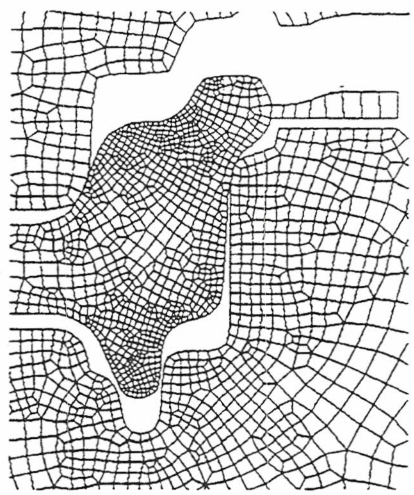

Fig. 7 - Numerical simulation of blank positioning

The reference temperature and the heat transfer

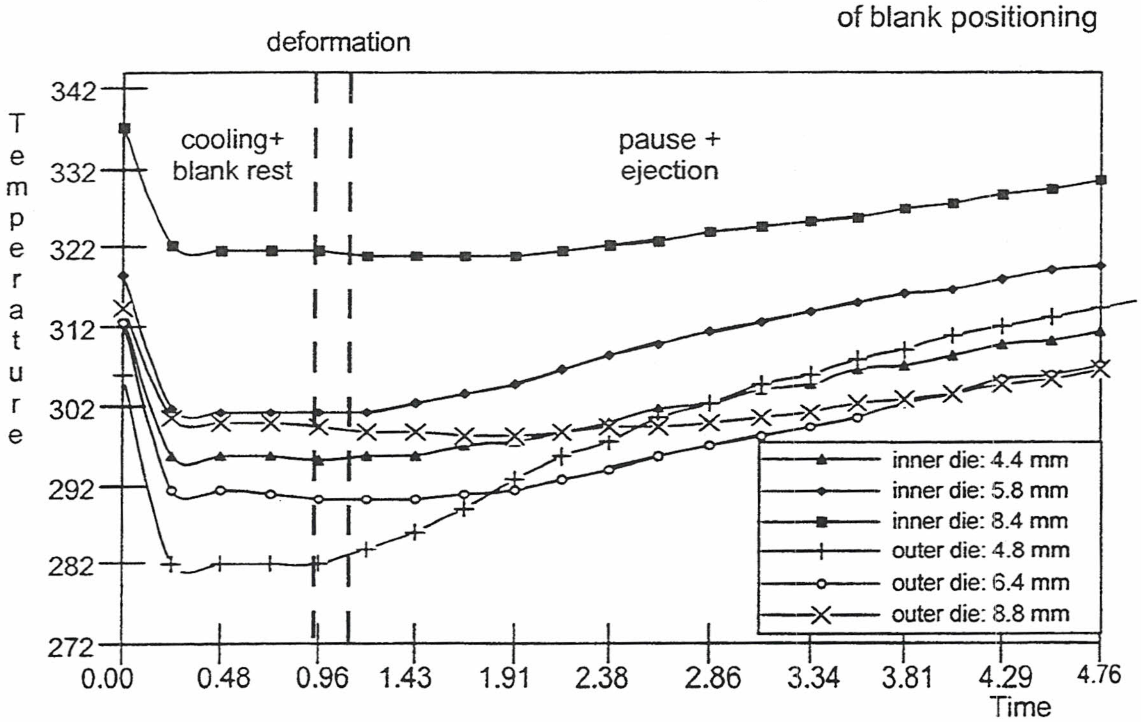

Fig. 8 - Experimental temperature Vs. time diagrams

coefficient are the thermal parameters varying from one phase of the simulation to the other.

3.4 *Measurement of temperatures*

Fig. 8 shows temperature vs. time diagrams as obtained from thermocouples in steady state conditions. It seems from curves relevant to thermocouples in the inner die that the die is always cooler close to the surface, which is opposite to what expected. No investigations have been conducted until now to understand this behaviour.

Curves relevant to the outer die seems more reliable. Also effects of thermal inertia are apparent in the diagram. Surface temperature is lower than inside temperature for most of the cycle because it is heated from inside and cooled from the environment. Surface is heated by the workpiece during deformation and pause, therefore heat flow inside the die change direction.

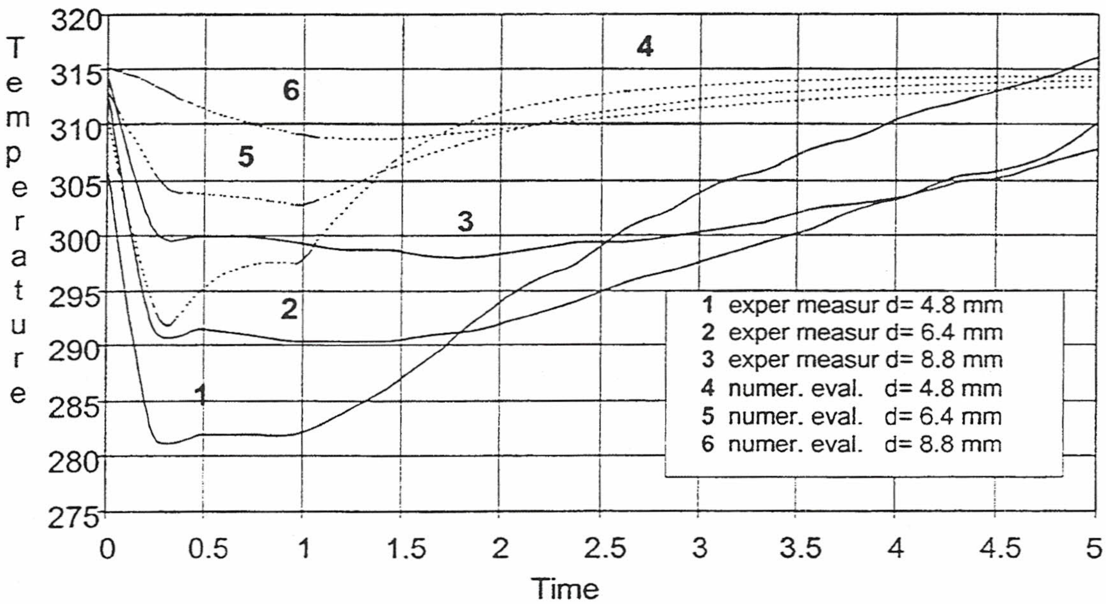

Fig. 9 - Comparison between experimental and numerical curves

3.5 *Inverse analysis*

- Inverse analysis is aimed at fitting results of the numerical simulation to measurements. For the reasons presented at the preceding paragraph, only the outer die is analysed. The numerical simulation used to decide thermocouple positions is tuned to approximate experimental curves. Inverse analysis is developed trying different values for the following parameters:
- heat transfer coefficient at interface between workpiece and tool,
- coefficient of conductivity of die material,
- temperature distribution inside the die at the beginning of the simulation.

Heat transfer coefficient is mainly important during plastic deformation and spraying. Heat transfer is low in the other phases and variations of this parameter slightly influence die temperature.
A value found in literature for thermal conductivity of die is the starting value for a sensitivity analysis where it is varied of ±20%.
As concerns the third item, only trial and error procedure is possible, modifying values and pattern of temperature distribution.

4. Results

The best approximation of experimental curves is shown in Fig. 6. Based on the relevant simulation, the maximum temperature predicted on the surface is 471°C at the end of deformation, the minimum value is 206°C after cooling, both on inner die. Maximum temperature after cooling is 339°C in the inner die, at about 15 mm from the surface,
The main problems to improve approximation are, as follows:
- prediction of the pattern of temperature distribution inside the die,
- prediction of the mean values of thermal characteristics of die material close to the surface, where thermal gradient is highest.

Possible ways to improve results are:
- thermocouples closer to the surface, for a more accurate study of temperature peaks,
- a few thermocouples distributed in the die, to have information on boundary conditions.

5. Conclusions

The paper presents a procedure made up of experimental analyses and numerical simulations to evaluate the thermal field inside forging tools. The procedure is applied to the finishing dies of a chain roll.
An inverse analysis based on measurements of temperature is used to improve reliability of a numerical simulation to estimate the thermal field inside a forging die.
The main results are (i) approximate replication of temperature Vs time curves from thermocouples embedded in the die and (ii) estimation of maximum temperature at the die surface.

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