INFLUENCE OF COOLING PARAMETERS ON THE SURFACE LAYER STRUCTURE OF HOT WORKING TOOLS

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Abstract

The surface layer of hot working tools is subject to alternating thermo-mechanical loads during forging. It experiences a fast increase in temperature on contact with the heated billets, followed by a steep temperature decline during application of the spray-coolant. This can lead to a cyclic surface rehardening of the tool surface layer due to the formation of a martensitic structure, which can either delay or accelerate tool failure. The microstructural changes in the tool surface layer mainly depend on the thermal, mechanical and tribological loads during forging. The influence of these loads is of particular interest to understand the effect of cyclic surface rehardening. The goal of this research is to investigate the influence of cooling parameters on microstructural changes in the tool surface layer during die forging. Mechanical and tribological loads are kept constant while cooling parameters are varied. Three internal thermocouples are applied to forging tools to measure the base tool temperature. To keep the amount of lubricant in each forging cycle at constant levels, cooling and lubrication are separated by use of boron nitride as lubricant, which is applied by electrostatic adherence. For cooling, the duration of water application is varied while maintaining pressure and spray pattern. Four tools with different tool base temperatures are investigated and the influence of the thermal loads on the wear behaviour displayed.

Keywords: Bulk metal forming, cooling, surface zone rehardening, wear

1. INTRODUCTION

Forging tools are exposed to high process related thermo-mechanical loads, that result from frequent alternations between rapid heating of the tool surface area during forming and rapid cooling due to the relatively cold base material underneath. This is further increased by the cooling of the tools [1]. These loads can cause permanent damage to the tool surface area and ultimately lead to tool failure. The main reason for tool failure is predominantly the wear of the contours [2]. During forging, peak temperatures in the thermally highly stressed tool areas exceed the tempering temperature of the tool material, thus softening the tool surface layer [3]. The softening of the material in the tool surface layer results in wear. A heated work piece is placed in the engraving, forged and finally taken out. The temperature rises to its peak value during contact of the up to 1250 °C hot work piece and the tool, with heat being transferred from the first into the latter. Following the forming process, there is a considerable drop of temperature in the engraving surface after releasing the forming force and contact pressure. The tool starts cooling with the warm work piece still in the die. Due to thermal conduction, the heat flows into the colder base material below the heated zone and thus reduces the contact temperature in the surface. After removing the work piece, the temperature of the engraving surface drops due to radiation and convection. Finally, the cooling lubricant is sprayed into the engraving, cooling the tools below to tool base temperature (i.e., minimum temperature per cycle) and exposing them them to additional thermal stress. Afterwards, the temperature of the engraving surface once again reaches the set base tool temperature and the next work cycle begins [4]. The base tool temperature can be adjusted by the billet temperature, the amount coolant applied, the pressure contact time, the overall length of a forging cycles and the tool pre-heating.

In metallographic analysis of forging tools, rehardened tool surface zones often appear as white layers. They form when the tool surface area is exposed to high temperature gradients exceeding the material specific austenite start temperature in combination with cooling above a critical speed [5]. The effects of rehardened zones on the tool wear is controversially discussed in literature. Rehardened zones are often seen as tool damage [6]. Some studies compare the rehardening of the tool surface layer to a heat treatment that strengthens the tool surface area [7] and refer to the potential of the special wear resistance when exposed to abrasive stress [8]. It is shown in [9] that under sufficient conditions, surface zone rehardening happens instantly and can be detected after only a few forging cycles.

The investigation of the microstructural changes in the surface layer of hot forging dies is of great importance to better understand the effect of cyclic surface rehardening. In order to achieve the objective, in this investigation different stationary tool base temperatures are realized by varying the spray cooling parameters. The temperatures are measured with thermocouples. To keep lubrication at constant levels, coolant and lubricant are applied separately. This enables a precise cooling by controlling the amount of coolant introduced per time and area.

2. MATERIALS AND METHODS

2.1. Tools

A rotationally symmetrical tool is selected for forging tests (**Figure 1**). The mandrel surface area is subject to high thermal loads during forging, especially at the convex radius. Tools are made of hot working tool steel AISI H11 and heat treated to 48+2 HRC. Previous research has shown, that these tools display the essential structural changes and the associated wear due to abrasion and plastic deformation, which mainly occurs on the convex tool radius [7]. High contact pressures and thermal loads are expected in these areas due to the relatively long time of contact and the deep penetration of the tool into the work piece. To characterize the cyclic thermal loads, thermocouples are inserted into selected tools. The recording of the temperature takes place continuously over the entire forging process during the heating and cooling phases. Encapsulated Type K thermocouples with a diameter of ø1.5 mm are selected for the machined tool cavities with a diameter of ø1.6 mm (**Figure 2**) up to a distance of 3 mm to the tool surface. The thermocouple wiring is led out from the tools laterally (**Figure 2**, right). Thermal paste is applied to increase the heat transfer and decrease reaction time between the tool and the thermocouples.

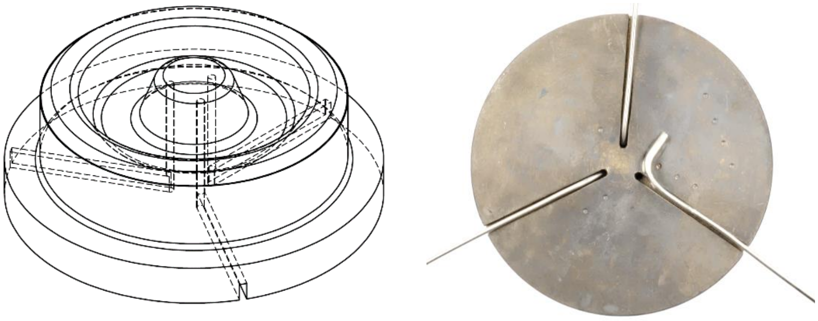

Figure 1 Thermally loaded tool with channels for thermocouples

2.2. Cooling and Lubrication

To carry out forging tests with different cooling gradients while maintaining constant amounts of lubricant, cooling and lubrication are separated in place of the industrial standard of fluid-based cooling lubricant. The same spray nozzle and constant spray pressures are used throughout all tests and only the spray duration is varied. The overall forging cycle times are adjusted to 8.4 s, which is the minimum possible time at maximum spray cooling. Before and after water spraying, air is sprayed on the dies to remove scale and excess water.

Electrostatic powder application technology is used for lubricant application. Powdered boron nitride (co. Henze BNP, type HeBoFill LL-SP 120) is applied as a lubricant. Puppa et. al. [10] showed, that this type of lubricant application can significantly reduce tool wear. Lubrication is carried out with a powder coating system (co. ITW/GEMA Surface Technology). Due to the functional separation of the cooling and lubricating process, the process is carried out in two stages, with stage I for cooling and stage II for lubricating the tools.

2.3. Forging

Fully automated serial forging tests are carried out on an eccentric press (co. Eumuco, type Maxima SP 30d) with a maximum nominal force of 3150 kN. All tools are preheated to a base temperature of 200 °C using heating cartridges. During forging, the tool temperature depth profiles change depending on the different cooling parameters. Stationary temperature values are reached after about 20 forging cycles in most cases. Blanks made of steel AISI 1045 are used as billets. Before forging, the billets are heated to a temperature of 1200 °C in a continuous induction furnace for all tests. The heated billets are transported automatically from the push-through furnace into the press by a robot. After each forging cycle, the formed billets are ejected. Then the tools are cooled and lubricated before the initiation of the next forging cycle as stated above. All forging dies are loaded with 50 forging cycles.

2.4. Wear Evaluation

In order to examine the tool rehardening and formation of white layers, the structures of the tool surface layer are examined metallographically. The tool mandrels are separated mechanically by a wet cut-off grinder to characterize the surface layer cross section without the inducing further thermal stress, e.g. by sawing. For metallographic microstructure analysis, the samples are embedded, polished and etched with 10 % alcoholic nitric acid (10% HNO_3). The sample microstructures are then analysed with a light microscope (co. Reichert-Jung, type Polyvar Met).

3. RESULTS

3.1. Cooling Parameters

The cooling is carried out with an air-water mixture, which is applied to the tool surfaces using a spraying system (co. Gerlieva). Spraying parameters such as pressure and duration can be regulated during the spray cooling via a control unit. The spray parameters are regulated in such a way that four different tool temperature profiles are realized. Therefore, tools equipped with thermocouples are used to determine fitting spraying parameters for each base temperature, which are shown in **Table 1**.

Table 1 Parameters for spray cooling

Target base temperature (°C)	100	200	300	400
Spray nozzles	co. Gerlieva, type 300-55365			
Spray nozzle distance (mm)	50			
Spray area (mm)	Ø 80			
Spray volume	15,4 ml/s at 1 bar coolant pressure			
Coolant pressure (bar)	4			
Pre-blow time (ms)	100			
Coolant spray time (ms)	1000	430	250	0
After-blow time (ms)	50			
Measured base temperature (°C)	110	200	300	350

Figure 2 shows the temperature measurements of the thermocouples for the four cooling parameters, each starting at 200 °C. While 200 °C base tool temperature (i.e., minimum temperature per cycle) is reached instantly, it takes about 20 cycles for temperature values close to 100 °C and 300 °C. 400 °C base tool temperature cannot be achieved even without coolant, as much of the thermal energy dissipated into the air. Therefore, the highest measureable base tool temperature at 3 mm beneath the tool surface with a forging cycle time of 8.4 s is 350 °C, while peak temperatures of about 380 °C are measured. It can be observed that the high tool base temperatures (300 °C and 400 °C) are closer to their peak temperature, thus reducing temperature gradients during each forging cycle.

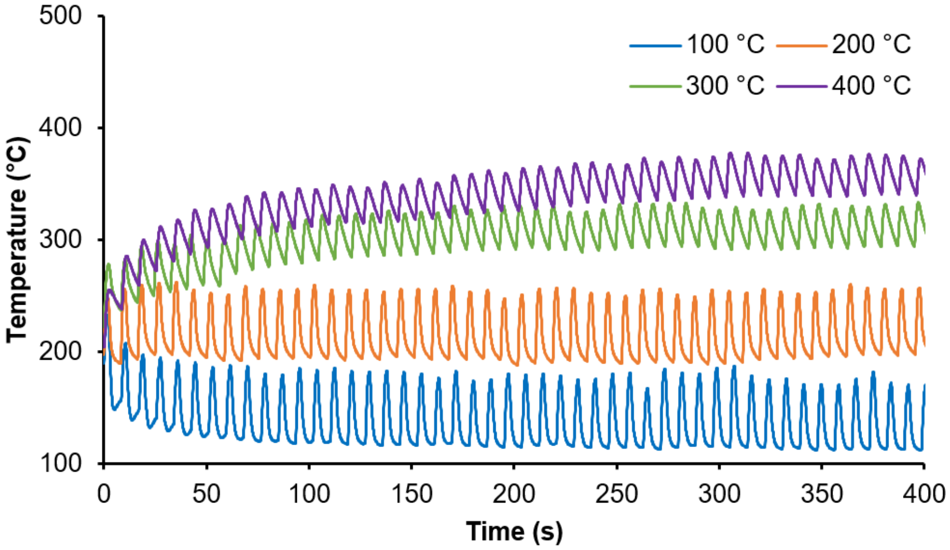

Figure 2 Temperatures during forging 3 mm below the mandrel surface

3.2. Metallographic Analysis

The tools are prepared after forging and cross sections of the mandrel are taken to examine the surface zone rehardening. The micrographs of cross sections displayed in **Figure 3** show the formation of thick white layers at higher temperatures. The maximum values for visible zone thickness are at about 100 µm for the tools at 300 °C and 400 °C target base tool temperature.

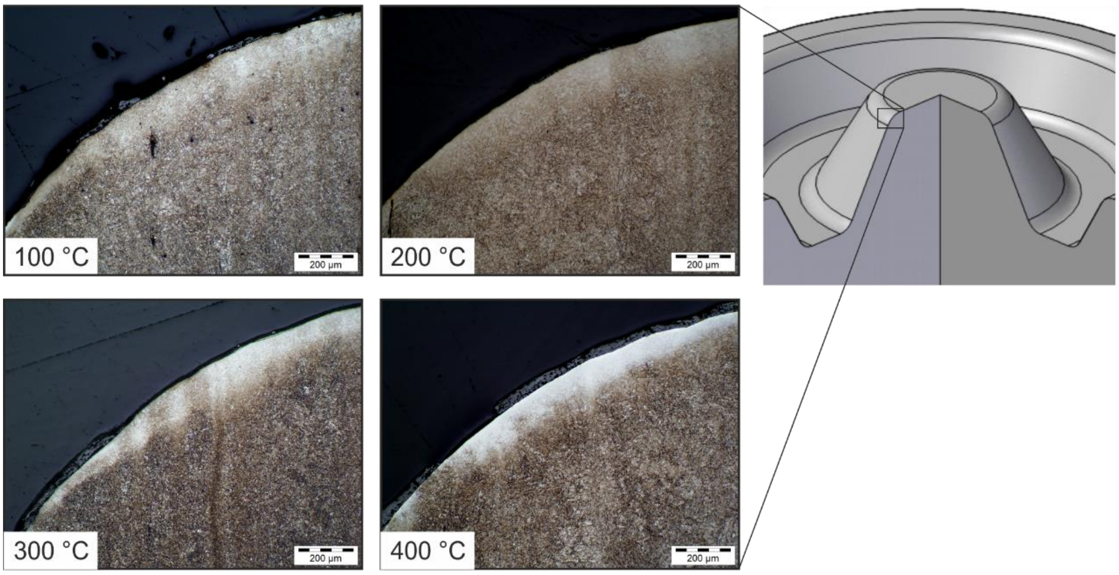

Figure 3 Micrographs at the convex mandrel surface layer showing formation of white layers

In **Figure 4** the micro hardness depth distribution is shown. All tools have a base hardness of about 500 HV 0,1, starting at a depth of about 500 µm. A surface zone rehardening for 300 °C and 400 °C base tool temperature is noticeable with a maximum hardness of 614 HV 0,1. This correlates with the micrographs of **Figure 3**, in which a white layer can be observed. An annealed area with a softened microstructure is found below, while 100 °C and 200 °C only show the annealed area with no surface zone rehardening.

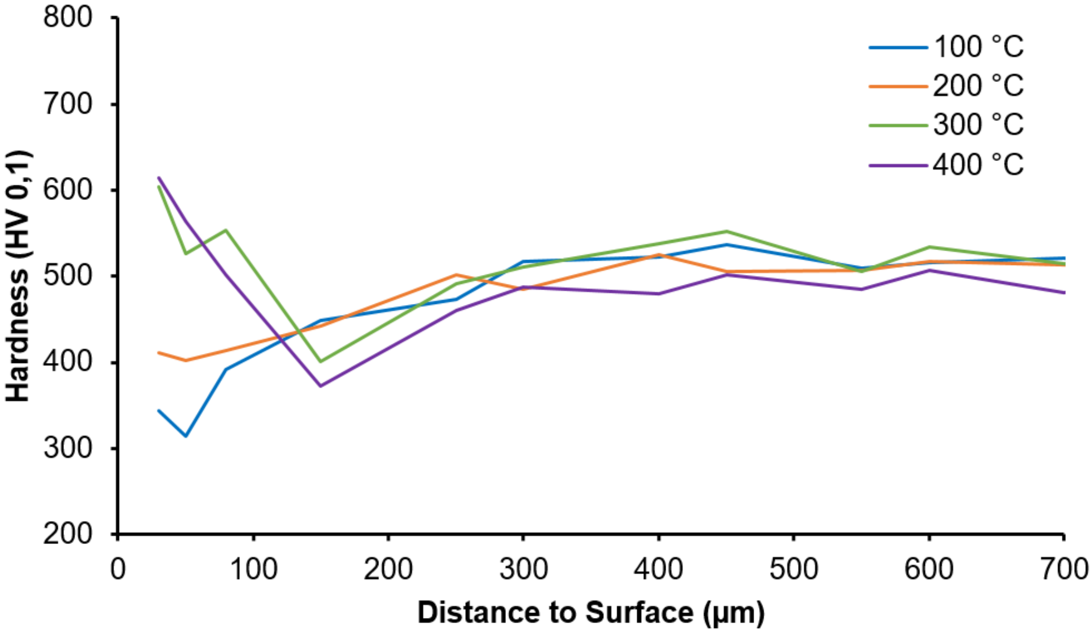

Figure 4 Micro hardness at the mandrel surface layer

4. DISCUSSION

When varying the tool base temperature, surface zone rehardening is predominantly seen at higher tool temperatures. While literature often cites a large temperature gradient as condition for tool surface zone rehardening and the formation of a white layer, this condition could not be verified in the trials of this paper. This is shown by high tool base temperatures having the smallest temperature gradients. Instead, high base tool temperatures seem to be mandatory in order to reach the austenite start temperature Ac_{1b} for any surface zone rehardening to occur. While thin white layers can be observed for all tools in the thermomechanically highly stressed mandrel area, they are much more pronounced for the tools forged at high tool base temperatures. Vice versa, a low tool base temperatures can reduce the formation of white layers and surface zone rehardening, or prevent them altogether. Thus, it is assumed that the thin white layers shown at 100 °C and 200 °C are the result of tempering.

5. CONCLUSION

The main objective was to investigate the microstructural changes in the surface layer of hot forging tools under varying cooling conditions. To better understand the formation of a rehardened area on the surface of forging dies, an examination of their formation under different base tool temperatures was carried out. For this purpose, a variety of cooling strategies were used. Forging tools were submitted to different thermal stresses for 50 forging cycles each. It was shown that higher tool temperatures promote the formation of hard white layers. These temperatures were reached in the mechanically loaded, convex mandrel area of a rotationally symmetrical tool, measured 3 mm from the surface.

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