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Metal flow and die wear in semi-solid forging of steel using coated dies

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Abstract:Thixoforging of steels is a potential forming technology, which aims at producing near-net-shaped components with good quality from high strength steels in one forging step. The thixoforging process parameters such as billet temperature, temperature distribution after reheating, argon gas pressure, transportation time and forging load were investigated on the thixoforging of non axis-symmetric parts of steel grade X210CrW12. The experimental and numerical study of the material flow and tool temperature load reveal the areas of intensive tool wear, thus being useful for further tool design. Hardened hot working steel X38CrMoV5-1 as a tool bulk material with protecting thin films of TiAlN/γ-Al_2O_3 shows good experimental results at 170 forging cycles.

Key words: steel; tool coating; thixoforging; process parameters; tool life time

1 Introduction

Thixoforging of steels is a promising technology which combines the advantages of conventional forging and casting. The metal forming itself takes place in the range of temperatures where the alloy is in a semi-solid state. The thixotropic material behaviour leads to material flow with low forces. This makes it possible to produce complex geometry parts in one forming step with loads much lower than in conventional forging. Comparing thixoforging with traditional casting the forming temperatures are lower leading to porosity and shrink reduction. Due to the high forming temperatures thixoforging of steel reveals technical and scientific challenges, which is the reason of its seldom use in industry[1−3]. As the temperature range in which thixoforging could be successfully performed is relatively narrow (30−80 ˚C depending on steel grade[1, 3]), the time in which it is possible to perform thixoforging is relatively short, depending on the billet volume and process arrangement due to temperature losses. This narrow process window requires an accurate knowledge and control of process parameters. Long solidification time (up to 10 s depending on the geometry and volume of the part) leads to high thermal loading of the tool. The conventional hot forging tools and materials can’t withstand the combination of mechanical and high thermal loading, which leads to the necessity of a new tool concept design (metallic tool with a protective PVD coating).

The current work presents the results of an experimental and numerical study of the process parameters, material flow and die wear in steel X210CrW12 thixoforging. The first thixoforging results were mentioned in Ref.[4].

2 Tool material and coating procedure

The tool bulk material X38CrMoV5-1 hot working steel was hardened to HRC 55. To improve the supporting effect of the bulk material the dies were additionally plasma nitrided so that the dies surface has a hardness of approximately HRC 70. The last step was coating the dies in an industrial MSIP (Magnetron sputter ion plating) coating unit. The dies were coated using four cathodes in a two by two dual cathode arrangement on a CemeCon CC800/9-SinO$_x$ coating device. To assure a sufficient adhesion of the γ-Al_2O_3 coating a 4 μm-thick ($Ti_{0.75}Al_{0.625}$)N bond coat was applied. The deposition of the 2 μm-thick γ-Al_2O_3 top layer was done by using two aluminium targets. The argon flow was kept at 200 cm^3/min. The oxygen partial pressure was automatically set by adjusting a voltage of 530 V at the cathodes. During deposition the dies were rotated to ensure a constant film thickness distribution. Before deposition the dies were heated and plasma cleaned in argon atmosphere. For this substrate cleaning process, an MF-power source was used. The PVD (Physical vapour deposition) tool coating development and design were discussed in details in previous publications[5−7].

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3 Thixoforging experiments and equipment

In order to investigate the steel thixoforging parameters and wear of the coated tools, a set of two experimental series were performed. For the first experimental series of 90 and the second of 170 forging cycles the tools have the same coating and similar geometries.

3.1 Billet material and heating procedure

X210CrW12 billets (d=78 mm, h=114 mm) were used. The billets for thixoforging were heated up in a vertical induction heating unit (maximum power of 50 kW) in a protective argon atmosphere. The billets temperature during the heating was controlled by 2 thermocouples placed in the centre and at the edge of the billet as shown in Fig.1. The billets were heated up using a three step power-time control strategy. The first step was performed at the maximum power of 45 kW in order to reach the temperature for the semi-solid state in a short time. Then the power was turned down to 19 kW and then to 11 kW to support the billet edge temperature while the inner layers of the billet get the heat by conduction. The billets 'softness' after the heating process (370 s) was checked by the so called 'cutting test'. The target temperature was 1 260 ˚C. This three step power-time heating strategy leads to the heating temperature of 1 240 ˚C up to 1 270 ˚C (approximately 10% to 45% of liquid phase by DTA) in the X210CrW12 billets (d=78 mm, h=114 mm). The reason for such temperature variation could be due to the differences in billet's chemical composition in combination with a varying argon pressure value (the induction heating unit was not gas isolated). Nevertheless this heating strategy was successful for heating billets for thixoforging. After heating the billets were manually transported with grippers to the forging die. Transportation time varied between 6 to 12 s. Even with the transportation time having this wide range (6 to 12 s) it had no noticeable influence on the repeatability of the process.

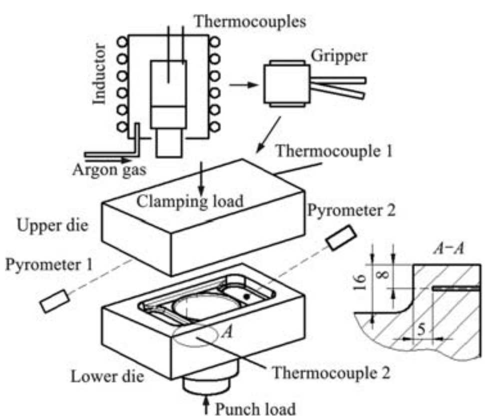

Fig.1 Schematic view of experimental set up (unit:mm)

3.2 Thixoforging procedure

The CNC hydraulic press of 6.3 MN with ejector punch of 1 MN was used for these thixoforging experiments. After placing the billet inside the lower die the upper die was closed (clamping load at Fig.1) and the injector punch was moved upwards (punch load) thus performing a thixoforging operation.

A closed die scheme was used for thixoforging of non axis-symmetric X210CrW12 parts.

After heating the billets were manually transported, with the help of a gripper, to the dies. The dies were preheated up to 250 ˚C. The dies temperature was controlled by 2 pyrometers and 2 thermocouples. Dies were lubricated with a graphite-water emulsion before each forging cycle.

The press control program stopped the working punch when the pressure reached 170 MPa and kept the part under that pressure for another 8−9 s to ensure that the solidification process is complete. The components inner defects were examined by X-ray and no porosity or other defects were detected.

All in all 260 components were thixoforged in 2 pairs of the dies.

The experimental results and parameters were described in details in the previous publication of the authors[4].

4 Process simulation model

The objective of the simulation was to model the temperature distribution in the tools and the component, predict the component's flow front and estimate the tool wear.

4.1 Rheological model

The rheological model for steel X210CrW12 was based on the previous investigators results which were presented in Ref.[8]. The obtained flow stress curves vs logarithmic plastic strain at different temperatures are shown in Fig.2. The curves of specific heat capacity vs temperature are shown in Fig.3.

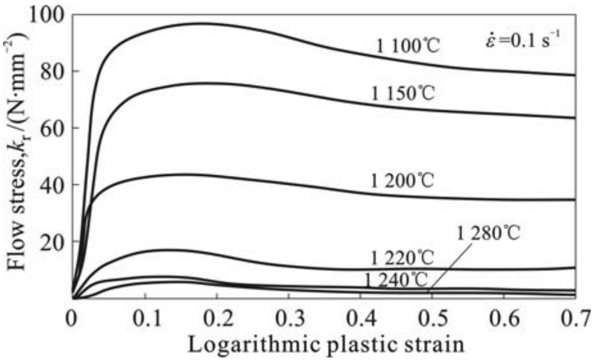

Fig.2 Curves of flow stress vs logarithmic plastic strain for steel X210CrW12 at strain rate of 0.1 s^{-1} and different temperatures[8].

All experimentally obtained rheological data [8] are given in table form for rheological model in Forge®.

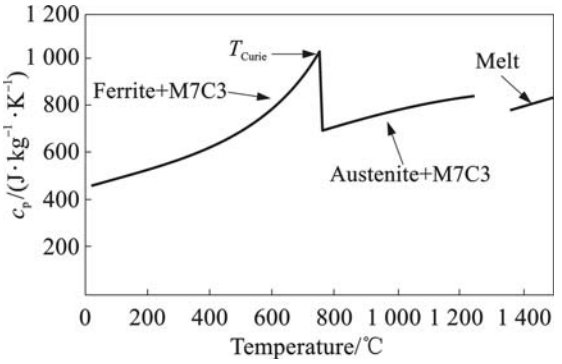

Fig.3 Curves of specific heat capacity vs temperature for steel X210CrW12[8]

4.2 Discretization

A 3D computer simulation was performed in Forge® 2008. As a tool geometry has 2 symmetry planes, for computation only a one quarter of the tool geometry was used (see Fig.4). The initial mesh was generated using the automatic mesh generation function. Quadratic six-node triangular elements were used for creating initial surface mesh, which was transformed into a tetrahedral volume mesh (see Fig.4) either for the billet or for the deformable dies. Various mesh refinement rates were tested for solution convergence before final selection of the initial mesh parameters.

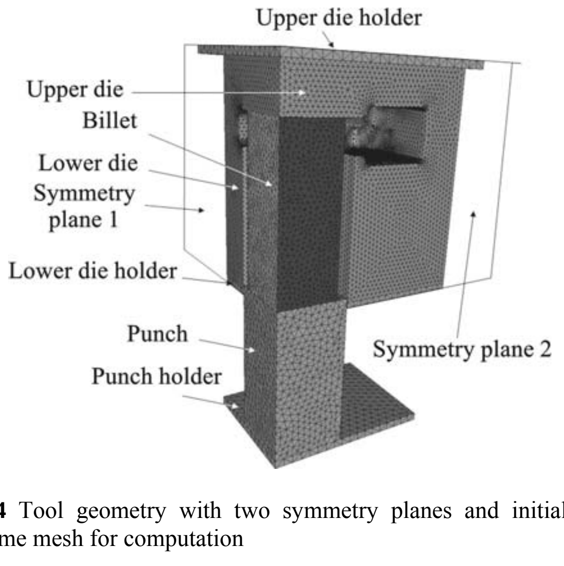

Fig.4 Tool geometry with two symmetry planes and initial volume mesh for computation

The simulation was performed in 2 steps: cooling of the billet in the air during transportation (see Fig.5) and thixoforging operation with this billet.

4.3 Wear model

The wear calculation in Forge® 2008 is based on the simple model:

$$W = \int \sigma_n v_t \, dt \tag{1}$$

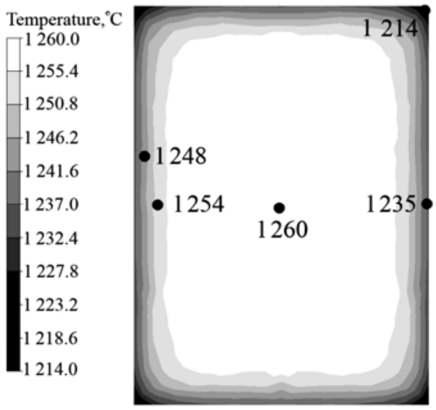

Fig.5 Predicted billet's temperature distribution in axial cross-section after being cooled 6 s in air

where W is a wear intensity, MPa·mm, and the calculated results can be estimated only qualitatively; σ_n is the normal stress and v_t is the tangential work piece velocity (the velocity with which a work piece moves along the tool).

In the future versions of Forge® an Archard's model of surface wear[9] will be introduced, which includes the influence of material hardness：

$$W = \frac{KFL}{H} \tag{2}$$

where W is the total volume of wear; F is the normal load; H is the hardness of the softest contacting surfaces; L is the sliding length; K is a dimensionless constant, which shows a measure of the severity of wear. Typically for 'mild' wear, $K \approx 10^{-8}$, whereas for 'severe' wear, $K \approx 10^{-2}$.

Eq.(2) seems to be more appropriate in case of the metallic thixoforging tools wear simulation when the dropping of die's material hardness becomes relevant due to the high process temperatures.

5 Results and discussion

5.1 Cooling of billet during transportation

After being cooled 6 s in the air, billet's cylindrical surface has a temperature of 1 235 ˚C which corresponds to approximately 5% of liquid phase (by DTA). The billet's edges have temperature of 1 214 ˚C and are already in the solid state.

5.1.1 Material flow

In the computer simulation the material flows with a smooth flow front starting with conventional upsetting and then flowing to the sides of the dies (see Figs.6(a), (c), (e)).

To compare the simulated material flow with the real one, a series of so called 'step-shooting' experiments was performed. The forming punch was stopped in different positions, so it is possible to observe how the material is flowing inside the die and which reas are filled first (see Figs.6 (b), (d), (f)). The material starts to flow to the sides with an uneven flow front (see Fig.6 (b)). This might happen because a jet of semi solid slurry flows through the selective break-ups of the harder skin, which might appear due to the radiation heat losses during the billet's transportation. At the final stage (see Fig.6 (f)) the die is completely filled. A one phase material model was used for simulation in Forge®, which is the reason why it can't predict the material flow when the liquid and solid phase movement is involved.

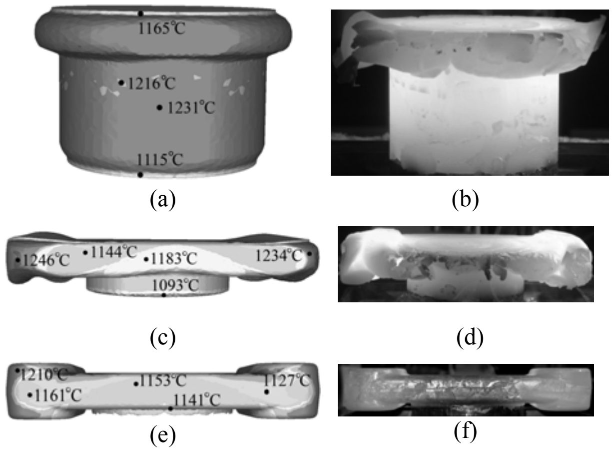

Fig.6 Computer simulation of material flow ((a), (c), (e)) and results of step shooting experiments ((b), (d), (f))

The experimental and computer simulation (Forge®) values of the punch load vs stroke are shown at Fig.7. The difference between the simulation and experimental curves in the region 50−85 mm of the punch stroke must be explained by the differences in the simulated and experimental material flow (see Fig.6). However, it is assumed that the simulation will be good enough to identify the areas of most critical die loading in terms of temperature and abrasive wear.

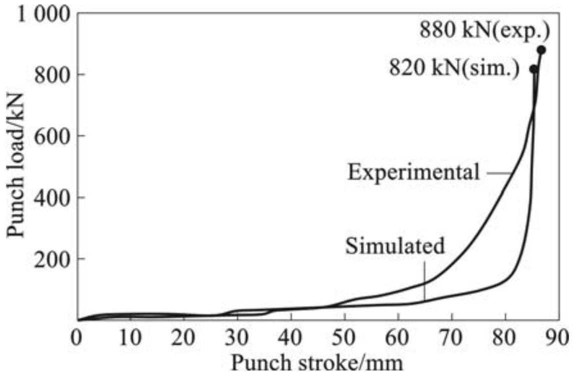

Fig.7 Curves of experimental and computer simulated punch load vs stroke

5.1.2 Temperature distribution in tool and tool wear

The simulated temperature distribution in the lower die is shown in Fig.8.

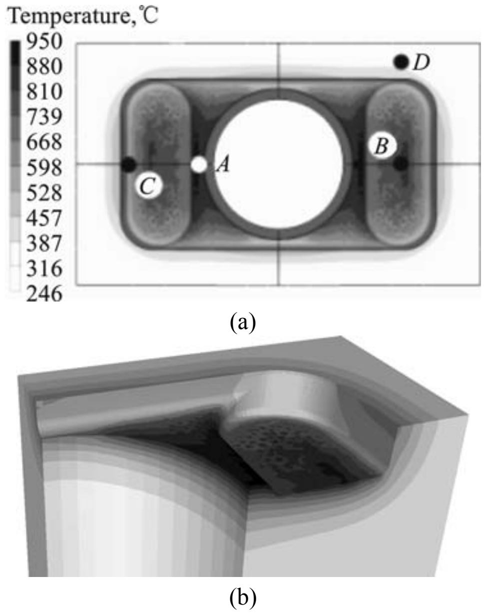

Fig.8 Computer simulation of temperature distribution after one thixoforging cycle of lower die (a) and its cross-section (b)

In order to estimate the influence of the temperature load on the tools surface, the dies temperature was controlled by 2 pyrometers and 2 thermocouples, which were positioned at 5 mm below the dies surface after each forging cycle (see Fig.9).

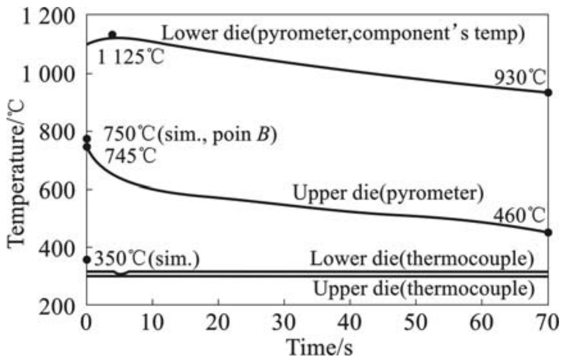

Fig.9 Curves of die temperature vs time measured after thixoforging cycle

The thixoforging cycle lasted 10 min and after 2−3 cycles the die temperature measured by thermocouples increased from 250 ˚C (die preheating temperature) to 290−330 ˚C and kept this value with small fluctuations (10−30 ˚C). The high temperatures (up to 950 ˚C) and temperature changes (dropping from 745 ˚C to 460 ˚C in 70 s, see Fig.9) create a high thermal load and thermo shock on tools.

The computer simulation (Fig.8) suggests the temperature at point D to be 350 ˚C, which is in a good agreement with the data obtained experimentally (thermocouples).The simulated tools surface temperature increases drastically during the material flow and reaches the highest value of 950 ˚C at point A (see Fig.8) at the end of a forging cycle. A few seconds after removing the component the temperature measured by the pyrometer at point *B* reaches 745 ˚C similar to the value suggested by the computer simulation (750 ˚C).

The lower die is chosen for tool wear investigations since it has longer contact time with the billet and shows a higher wear. The simulated surface wear of the lower die surface is shown in Fig.10. At points *A*, *B* and *C*, the simulation predicts no wear. Only at the region of point *E* the wear is significant. The heat effects are not taken in the account in wear model (1) in Forge® 2008.

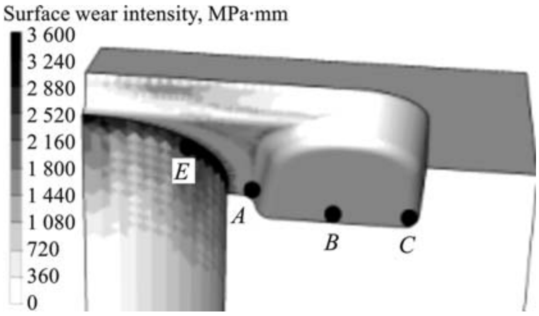

Fig.10 Simulated surface wear intensity of lower die (only for qualitative estimations)

The hardness of die bulk material X38CrMoV5-1 drops significantly when the material is heated up to more that 600 ˚C [10]. If to compare the predicted wear (Fig.10) with temperature distribution in the die (Fig.8), the area of point *A* seems to be the most 'weak' point.

The SEM images of the lower dies and cross-section polish for the given positions are shown in Fig.11. Positions 1, 2, 3 (Fig.11) correspond to points *A*, *B*, *C* shown in Fig.8.

Position 1 is the area where the material flows along the edge with high normal stresses. Local high temperatures of 920−950 ˚C (taken from the computer simulation) lead to the situation when the die bulk material looses its hardness. The mechanical damage on the tool surface occurs while the forming pressure exceeds the local strength of the tool material at a given local temperature (hot strength). One can observe a local plastic deformation of the tools edge and abrasive wear after 170 cycles at position 1. At the cross-section polish one can observe that the bulk material is partially removed, forming a triangle form instead of initial 4 mm radius. This might happen during the billet material flow along this edge to the combination of high local temperatures (see Fig.8, point *A*) and low bulk material hardness. Comparing the upper and lower dies similar positioned edge (position 1) the upper dies edge shows much less mechanical damage. As the material flow and billets temperature might be the same, the die volume and geometry has a critical influence on the occurrence of mechanical damage. Since the lower die has a hole for the working punch it leaves a small bridge (position 1). The heat gained from the billet can't dissipate as fast and remains there causing higher local temperatures. On the other hand, the upper die has no hole, furthermore a higher bulk material volume results in a better heat transfer to the inner layers of the die and thus has less mechanical damage in the end.

Position 2 shows no mechanical damage even the coating looks intact after 170 forging cycles. The measured and simulated local temperatures are lower (around 750 ˚C) than those at position 1 (950 ˚C). Moreover, the material doesn't flow along this area, instead it flows perpendicularly to the surface direction. The experimental 'step-shooting' and the computer simulation suggests such material flow (see Figs.6 (c)−(f)). Moreover, the surface has good heat dissipation possibilities (in this case a plane surface) in combination with low tangential forces ensuring the prolongation of the tool life.

At position 3 the coating remains intact after 170 forging cycles. Simulated local temperatures are about 480 ˚C (see Fig.8, point *C*). Here the material has a relatively short flow length and reaches the area of position 3 only at the end of the forging cycle. The cross-section polish of position 3 shows only mechanical damage on the top. This is the area where the upper and lower die come in contact. Mechanical damage might have occurred when the solidifying material flows between the dies during the experiments with low clamping load. Although the mechanical damage at position 1 is visible and the geometry form of the tools edge radius (4 mm) changed into a triangle (with the sides of 3 mm) the dies can still be used for more forging cycles.

The examined rest of the dies surface (not shown in the figure) shows no wear and looks intact after 170 cycles. Damages can occur in a form of corrosion, abrasion or adhesion due to the contact with work piece material, especially with the steel melt when it comes to semi-solid state. The observed adhesion of work piece material is very low which demonstrates the chemical inertness of the coating. Another typical metallic tool damage is the propagation of a hot crack, which occurs after a great number of thermo shock cycles as a consequence of the thermal fatigue [5]. After 170 thixoforging cycles no cracks are visible on either of the dies.

6 Conclusions

1) Experimental and computer simulated study of the material flow and tool temperature load reveal the areas of intensive tool wear and mechanical damage. Hardened hot working steel X38CrMoV5-1 as a tool bulk material with protecting thin film crystalline TiAlN/γ-Al_2O_3 shows good results. It can withstand

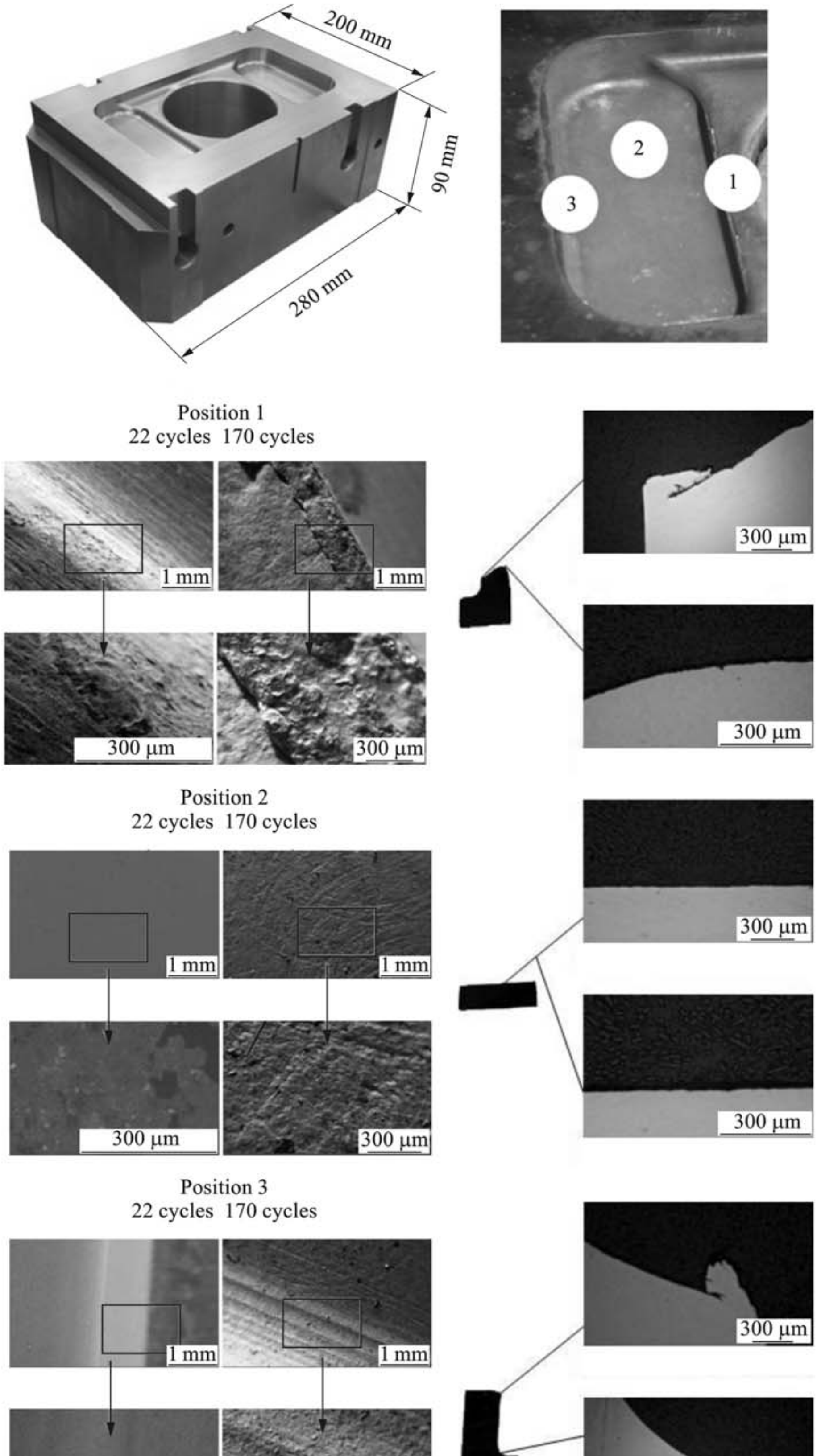

Fig.11 Lower die and SEM images of close-up (scale corresponds to 1 mm (upper images at each position) and 300 μm (lower images at each position) of three positions after different numbers of thixoforging cycles. To the right the cross-section polish (scale corresponds to 300 μm) after 170 cycles is shown for the given positions)

mechanical load, with high adhesion and oxidation resistance.

2) For the tool life prolongation either the edge radius could be enlarged or the tool wall thickness could be increased in order to increase the local bulk volume and thus increase the temperature transfer into the inner layers of the tool.

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