STUDY ON CROSS SCALE THERMODYNAMIC COUPLING BETWEEN INTERFACIAL HEAT TRANSFER AND DIE FAILURE MECHANISM IN METAL THERMOFORING PROCESS

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ABSTRACT*: As the research under the condition of high temperature and high pressure, interfacial heat transfer in the mould failure and the effect of strengthening mould interface heat transfer behavior, investigate the micro mechanism of die failure, this article USES the Deform 3 d software of TC11 titanium alloy gear plate of the hot forming process of thermal coupling simulation and analysis of the forging die in three main failure mechanism of easy worn parts, the results show that the preheating temperature, within the range of 150 ~ 400 DHS C IHTC increasing eventually stabilised; However, when the deformation rate is greater than 0.1s-1, the surface treatment process of composite ceramic coating and polymetallic heat resistant layer is reduced. In contrast, polymetallic heat resistant coating is not easy to peel off when working at a high deformation rate, and still maintains a strong thermal resistance.*

KEYWORDS*: Interfacial contact heat transfer coefficient; Multi-scale; Thermal coupling; Die failure*

1 INTRODUCTION

There is a close relationship between interfacial heat transfer and die failure behavior. The existing research also shows that the heat load on the die working interface is the main cause of die failure. Therefore, strengthening the research on the heat transfer characteristics of the working interface of the forging die and discussing the failure mechanism of the hot-forming die on this basis can lay a theoretical foundation for the design of long-life and high-performance functional gradient die materials. As is known to all, metal oxidation is a common phenomenon in thermoforming processing. The degree of metal oxidation determines the heat transfer performance of the contact interface during thermoforming, and the strength of the heat transfer performance will affect the metal oxidation in turn [1].

2 LITERATURE REVIEW

Zhijin Lv believes that the extension of holding time during hot forming may cause the change of chemical composition of the blank, and the changed chemical composition will have a significant impact on the oxidation behavior of the blank [2]. N. Zhou et al. used this method to study the influence of oxide layer thickness on IHTC and the relationship between heating time of billet and oxide layer thickness [3]. Fundamentally speaking, the heat transfer between hot forming blank and die contact interface and the influence of interface heat transfer on die failure is a complex problem of cross-scale heat-force coupling. Javed Iqbal et al. simulated the interface heat transfer behavior between rough walls by using the non-equilibrium molecular dynamics method, and obtained the influence law of wettability of solid walls and roughness elements on the interface heat transfer between solid and liquid [4].

The innovation of this paper is that based on the measured test data of interfacial contact heat transfer coefficient, the thermally coupled numerical simulation of TC11 titanium alloy gear plate during the thermally forming process is carried out.

3 RESEARCH METHODS

3.1 Measurement of surface wear of forging die

As the contact time between the underdie and the forging billet is the longest, the load is more complicated and the working conditions are worse, the underdie is selected as the analysis object. After the final forging of 1300 pieces of blank was completed, the surface wear of the lower die (whose service life proved to be the shortest) was measured using the GOM ATOS II optical scanner. The technical specification of the scanner is: each scan

1400000 measuring points, the scanning volume is 250*200*200mm3, the scanning accuracy is 0.05mm. Through comparative analysis of the images obtained from the scanning part, it was found that the most severely worn parts appeared in zone 1 and zone 3 without considering the forging production batches.

There are different failure mechanisms in these parts of forging die, which have different effects on the failure of forging die. In order to find out the failure mechanism of the mold in these parts, the deform-3d software was used to conduct simulation, and the failure behavior and failure mechanism of the mold in these parts were analyzed by combining the statistical data of forging production and mold failure in enterprises.

3.2 Thermal coupling simulation of gear disc

In order to determine the failure mechanism of the three selected areas of the lower die in final forging, the information of temperature field, stress field and blank forming must be obtained first. First according to the technical documents in the process of forging, such as die forging press of the drawings, technical specifications and other information based on the mould (upper die and lower die), and 3 d finite element model of plunger workpieces, and then to convert these models to the STL format in turn into Deform 3 d software to carry on the grid, and set a boundary conditions and initial conditions of the model respectively, and then began to simulate.

When the temperature field of forging die is simulated, the forging die is assumed to be rigid body and the blank to be plastic body. When the stress analysis of forging die is carried out, the forging die is set as an elastic body and the blank is still a plastic body [11-12]. During the simulation, the initial forging temperature of the blank and the preheating temperature of the mold were set to 980 C and 300 C, respectively, and the ambient temperature was 25 C. That is to say, when the deformation rate of TC11 titanium alloy was 0.2s-1 (the pressure rate of the upper die was 20mm/s), the reference value of IHTC at each stage of the thermal forming was shown in table 1. The boundary friction condition between the blank and the mold is shear friction model and the friction coefficient is set to 0.3 (the boundary condition of hot forming with lubrication, the default of the system) [5].

Table 1 IHTC value of TC11 blank in final forging

Step	Molding process and time	Corresponds to the Deform set value	IHTC experimental value	Simulation steps
1	Forging stock transfer 8s	0.034N/sec/mm/C	35 W/(m^2*K)	81
2	For die forging 2s	4.22 N/sec/mm/C	4240 W/(m^2*K)	22
3	Die forging forming 1.7s	12.309N/sec/mm/C	12057 W/(m^2*K)	169
4	Forgings take out 32s	1 N/sec/mm/C	1000 W/(m^2*K)	324

In order to verify the rationality of setting thermal boundary conditions and the accuracy of simulation model, the measured temperature of thermocouple was compared with the simulation temperature of deform-3d. It can be seen from the analysis that the temperature variation trend of forging die in each forging cycle is basically the same. At the early stage of the forging cycle, there is a certain error between the measured temperature and the simulated temperature due to the instability of the actual initial state and the boundary condition of the die. After 5 continuous forging cycles, the measured results are in good agreement with the simulated results. It shows that the setting of IHTC value in table 1 is reasonable, and the simulation model is accurate and reliable in the simulation process of TC11 gear die forging.

After 9 continuous forging cycles, the temperature of the forging die basically reaches the thermal equilibrium state, that is to say, the blank and heat absorbed by the hot forging die is lost to the surrounding environment, and the forging die is in a stable state. Figure. 1 shows the comparison between the measured temperature at point A and the simulated temperature when the forging die is in A steady state (the 9th continuous forging cycle). The figure shows that stay in stock transfer, die forging and die forging forming stage, the measured temperature of the point A consistent with the numerical simulation of the temperature is almost, just after the final forging pick-up phase, cooling and lubrication and the measured temperature and the simulated temperature began to show some differences (simulated temperature slightly higher than the actual temperature), but overall the experimental data very well, further confirmed the simulation model and the rationality and the accuracy of boundary conditions are set. Since the forging die is in a steady state for most of the time when it works continuously, the simulation of temperature field and stress field of the forging die is carried out in the 9th forging cycle.

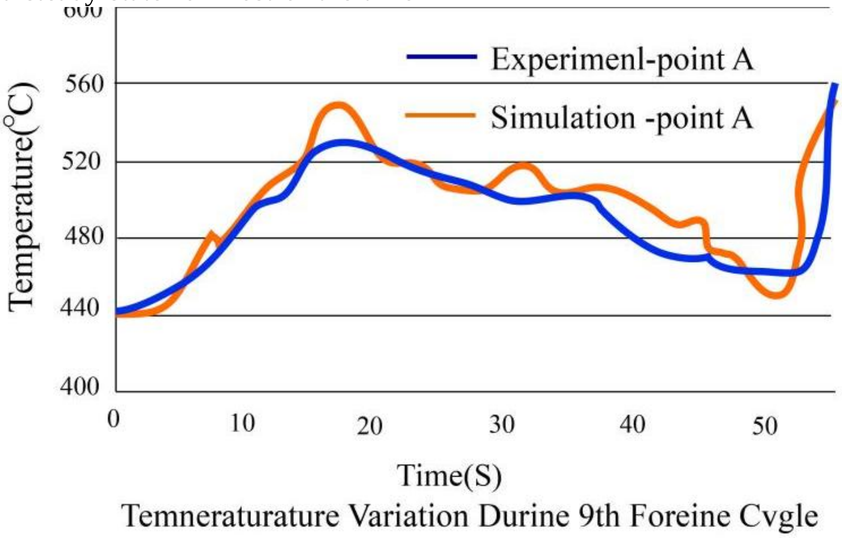

Figure. 1 temperature change during the 9th forging cycle

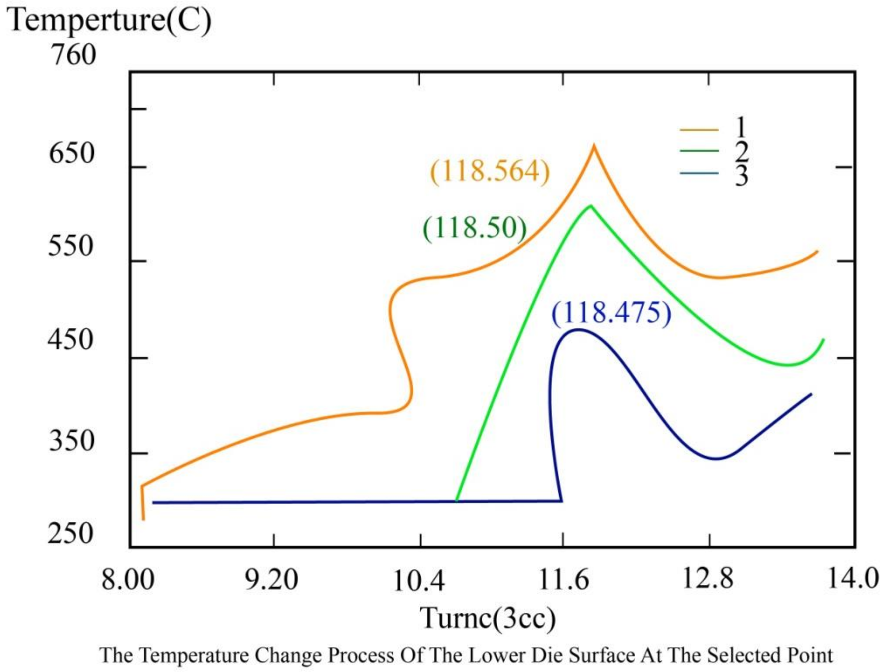

Figure. 2 temperature change process of the lower die surface at the selected point

As can be seen from the temperature change trend in figure. 2 the temperature change in zone 1 is the most drastic, followed by that in zone 2, and the temperature change in zone 3 is the most moderate. When the shape time reaches 11.8s, the surface temperature in zone 1, 2 and 3 reaches the maximum value of 664 C, 621 C and 475 C, respectively. These temperatures all reach or approach the tempering temperature of H13 die steel. According to the relevant data, it is found that when the tempering temperature of H13 steel is around 500 C, the hardness reaches the maximum. After 500 C, the surface hardness decreases rapidly with the increase of tempering temperature, as shown in figure. 3 [6].

Since the peak temperature of zone 1 and zone 2 during thermal forming is much higher than 500 C, it is easy for zone 1 and zone 2 to soften at high temperature in the process of thermal forming, resulting in plastic deformation and failure of the mold. It is pointed out in the literature that H13 die steel is easy to produce tempering brittleness in the temperature range of 400 ~ 500 C, resulting in a significant reduction in the impact toughness of steel. The peak temperature of the forging die in zone 3 is just in the tempering brittle zone of steel, so the surface of zone 3 of the forging die is prone to brittle cracking due to the insufficient ductility of the material. In addition, the test results in the third chapter of this paper also confirm that when the average temperature of the die interface is in the range of [400 C, 450 C], the forging die surface is prone to low-temperature oxidation. When the oxide layer grows to a certain thickness, it will crack and peel off from the surface of the die under the action of external forces, thus aggravating the wear of the forging die in zone 3.

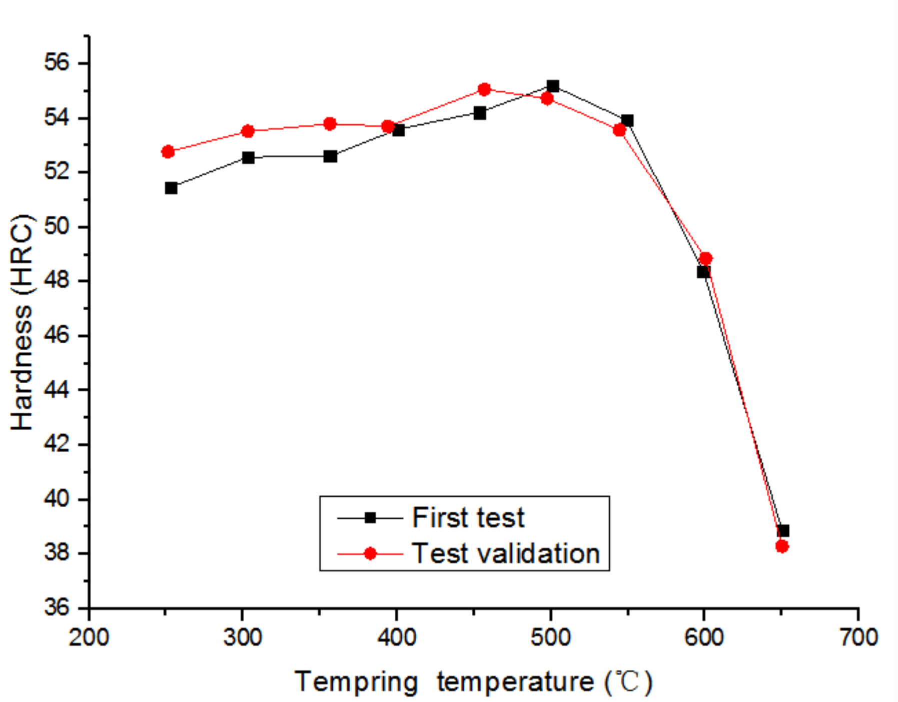

Figure. 3 relationship between surface hardness and tempering temperature of H13 steel

From forging die in three easy wear area equivalent stress along the radial direction of change, you can see that in the process of reducing death in 1 zone and 2 zone, equivalent stress values in radial flow direction (block) basic continues to fall, the equivalent stress of the center of the forging die minimum 1944.47 MPa gradually decreased to 376.68 MPa, arrive soon pressure after 3 area of up to 2400 MPa, after arriving in 3 area, equivalent stress values fell sharply again. Obviously, the equivalent stress changes most dramatically in area 3 and its vicinity, and the stress there is mainly mechanical stress. Under the alternating action of this mechanical stress, the surface of the forging die is prone to mechanical fatigue. The forging die is mainly affected by compressive stress in zone 1 and zone 2, while in zone 3 it is mainly affected by tensile stress. The compressive stress in zone 1 is the largest, about 3370MPa, and the tensile stress at the corner of zone 3 is the most obvious, about 2470MPa.

The results of previous analysis have shown that thermal stress is the main cause of damage and failure of forging die. Therefore, the following formula is then used to calculate the peak tensile and compressive stresses on the surface of the hot forging die in zones 1, 2 and 3. The peak tensile and compressive stresses of the dangerous points on the surface of the hot forging die are as follows:

$$\sigma_{max} = -\frac{E\beta\,(\Delta T)\ min}{1-\gamma}$$

$$\sigma_{min} = -\frac{E\beta\,(\Delta T)\,max}{1-\gamma}$$

Type: (Δ T) min is in hot forging die cavity surface and near surface temperature difference value of the minimum;

(Δ T) Max is hot forging die cavity surface and near surface temperature difference value maximum.

The elastic modulus (E), linear thermal expansion coefficient (β) and poisson's ratio (γ) of H13 steel were calculated by taking 2.10105MPa, 1.35 10-5 c-1 and 0.3 respectively. The peak surface temperatures of the forging die in zone 1, zone 2 and zone 3 T_d^{max} were calculated by taking the finite element simulation results in figure. 2, that is, T_d^{max} was 664 C, 621 C and 475 C respectively. The final calculation results were drawn in figure. 4.

Obviously, the maximum thermal stress of the forging die is in zone 1, and the peak tensile and compressive stress on the surface are 228.58mpa and 976.05mpa respectively. The thermal stress in zone 2 is slightly smaller than that in zone 1, which is 213.8mpa and 912.87mpa respectively. The surface tensile and compressive thermal stress values of zone 3 were the lowest, which were 163.54mpa and 698.34mpa, respectively, which were 65.04mpa and 277.71mpa lower than the peak tensile and compressive thermal stress values of zone 1. Therefore, when the hot forging die is working, the interface temperature changes have a greater impact on zone 1 and zone 2, and a smaller impact on zone 3 [7].

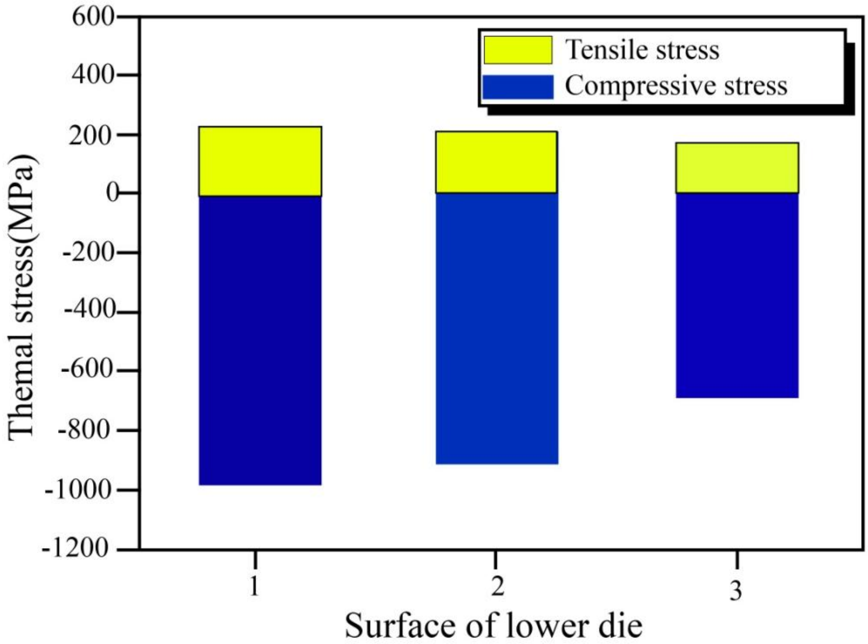

Figure. 4 calculation results of thermal stress on the surface of forging die

4 EMPIRICAL ANALYSIS

4.1 Failure mechanism analysis of forging die

The following wear mechanism plays a decisive role in the surface wear failure of the mold:

(1) Abrasive wear. Abrasive wear leads to die material loss, which is mainly manifested as several small particles peeling off the die surface. This wear occurs when loose or fixed abrasive particles or harder material protrusions (acting as local microblades) rub together in interacting units.

(2) Adhesive wear. The surface of the actual friction pair is uneven from a microscopic perspective. At this point, even if a small load is applied, the local stress on the real contact surface is enough to cause plastic deformation, in the plastic deformation of the microscopic region of the bulge or bump between atoms adsorption adhesion, that is, cold welding phenomenon. In the subsequent relative motion, the adhesive is cut off and transferred from one surface to another, resulting in adhesive wear on the die surface.

(3) Oxidative wear. Oxidation wear is the formation of oxidation film in the deformation area when the actual contact area of friction pair produces plastic deformation due to the action of corrosion environment. During the sliding process of the friction pair, the oxide film may peel off when it encounters the second bulge, reoxidizing the exposed surface. This repeated process of oxide film formation, peeling, regeneration and re-peeling causes the surface of the mold to be gradually oxidized and worn away.

(4) Thermal mechanical wear. Thermal mechanical fatigue wear is a kind of wear caused by partial loss of cohesion of die material. In hot forging die work, mechanical load and thermal load on the die chamber in a periodic pulse form function, make the surface of the chamber produces high mechanical stress and thermal stress, when the two stress mutual coupling and over mold material fatigue strength limit, can produce metal debris fell off from the substrate surface, thermal mechanical fatigue wear caused when hot forging die in large area of damage and wear another destructive factor is the permanent deformation of mould surface indentation and punch. In the design of forging die (especially the parts prone to plastic deformation) it must be ensured that the equivalent stress of the die

shall not exceed the yield stress of the die material [8-9].

4.2 Failure mechanism analysis of forging die surface

The wear on the surface of die cavity is a process of gradual change. With the increase of the number of forgings, the wear degree of die cavity surface is getting worse and worse, which eventually leads to the failure of the whole die. TESCAN Vega 3 scanning electron microscope was used to observe the wear condition of forging die in each wear area, and the failure mechanism of forging die in each wear area was analyzed by combining with the previous finite element simulation results.

The existence of mould fragments and abrasive oxide particles caused by thermal fatigue cracks is the main cause of increasing wear of abrasive particles. The wear rate of the surface layer depends on the hardness, thickness and wear resistance of the nitride layer. After the forging of 1300 products, the hardness of the surface layer of the forging die almost dropped from 800HV to 400HV, and the continuous decrease of hardness indicated that the cycling heat load on the surface of the die caused by alternating heating and cooling caused the softening of the nitriding layer. In the 2 zone of forging die, the time of contact with the hot forging is less than that in the 1 zone, so the stability of the surface nitriding layer is better. In the third zone, the friction between the blank and the wall of the die cavity is relatively fierce, and the stress concentration is generated in the area near the corner of the third zone. After forging about 1000 pieces, the nitrided layer gradually disappears, so the wear resistance in the third zone is not high.

4.3 Surface wear analysis of forging die

For every 200 forgings produced, the forging die was scanned as a whole to calculate the change rule of the wear amount of forging die with the number of forging pieces produced. It can be seen that the wear amount of forging die is small and the wear degree is stable in the early stage of forging. But when the output of forging reaches 1000 pieces, the wear degree of forging die increases rapidly. After more than 2600 pieces of forging, the wear of forging die gradually tends to be stable. The changing law of the wear amount of forging die volume can be explained as follows: in small batch forging, the wear amount of the die is small in the early stage of forging due to the protection of the nitriding layer on the hard and wear-resisting surface of the forging die. With the gradual increase in the number of forgings produced and the continuous enhancement of interfacial heat transfer, the surface wear of the forging die becomes increasingly serious. Due to the loss of die materials caused by wear, the die cavity size has become larger, the die cavity in the mass production pressure is much lower than the initial forging, therefore, the volume of forging die wear in the future with the further increase in the number of forgings will not continue to increase.

4.4 Experimental verification of thermal resistance effect of coating mold interface

In order to evaluate the effect of the die surface coating on the thermal forming metal interface heat transfer, the back heat conduction model was used to calculate the IHTC again, and their heat transfer efficiency was compared under various forging process parameters. Because the coating thickness on the mold surface is very thin compared with the overall size of the mold, the coating thickness is ignored in the calculation of IHTC to simplify the calculation process, so as to obtain the equivalent IHTC value. When the preheating temperature of the mold is 300℃ and the deformation rate of the blank GH469 is 0.04s-1, the equivalent IHTC value of the mold treated with conventional nitriding and surface coating at different initial forging temperatures is different.

Compared with the traditional nitriding heat treatment mold, the composite ceramic coating and the polymetal heat resistant layer mold have a strong barrier effect on the interfacial heat transfer, and the equivalent IHTC value is always lower. Among them, the equivalent IHTC value of the composite ceramic coating mold at this deformation rate is lower than that of the polymetal heat-resistant layer mold.When the average temperature of blank/mold interface reaches 500℃ and the deformation rate of blank GH4169 remains at 0.04s-1, the relationship between the calculated equivalent IHTC value and the insulation time is shown in figure 5 [10].

sensitive to the change of the blank insulation time. The IHTC value of billet decreased significantly when the billet insulation time increased. The significant decrease of IHTC is due to the formation of an oxide layer on the surface of the billet during heating and insulation, which impedes interfacial heat transfer in the subsequent thermal forming process. In contrast, the IHTC of composite ceramic coating and polymetallic heat-resistant layer mould is not sensitive enough to the change of heat preservation time of the blank. As the insulation time increased, the IHTC value decreased only slowly. When the heat preservation time of the blank is less than 20min, the influence of composite ceramic and polymetallic heat resistant layer on IHTC value is different to some extent, and the influence of composite ceramic coating on interfacial heat transfer is slightly greater than that of polymetallic heat resistant layer. However, after 20 minutes, their effects on IHTC gradually became consistent.

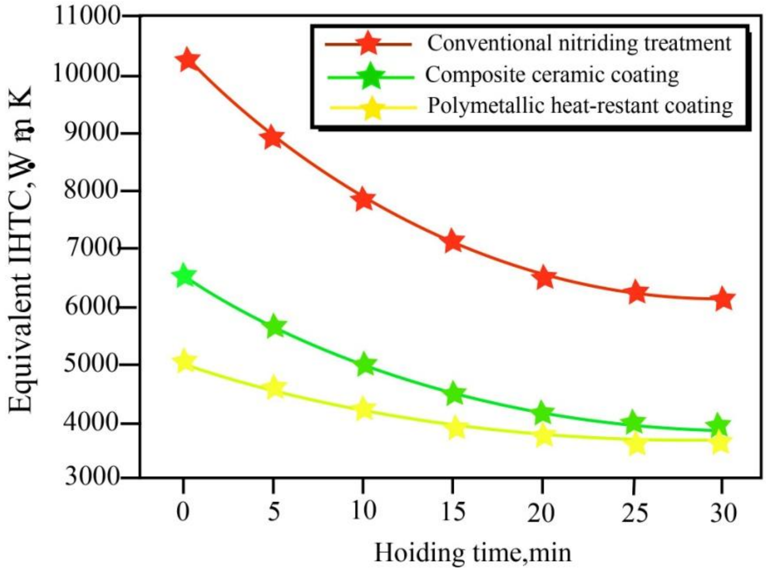

Figure. 5 variation of equivalent IHTC with insulation time

5 CONCLUSIONS

The failure of forging die is mostly directly or indirectly related to IHTC. The high IHTC value leads to a large peak temperature and thermal stress on the working surface of forging die, which is the "root cause" of various damage and failure of forging die. With the help of deform-3d software, thermal coupling simulation was carried out for TC11 gear plate die forging production process, and the failure behavior of contact fatigue and damage of H13 die steel under the action of thermal coupling was analyzed based on the statistical data of forging production and die failure in enterprises, and the main failure mechanism of forging die in the parts prone to wear was discussed. The surface of H13 forging die was treated with composite ceramic coating and polymetallic heat-resistant layer respectively. The results show that the composite ceramic coating and the surface treatment of polymetal heat resistant layer are two effective measures to reduce the IHTC and improve the heat condition of the forging die surface, which can be applied to different forging occasions. Among them, the thermal resistance of composite ceramic coating at low deformation rate is stronger than that of polymetallic thermal resistant coating, but when the deformation rate is greater than 0.1s-1, the composite ceramic coating starts to peel off, resulting in a rapid reduction in the thermal insulation effect. In contrast, polymetallic heat resistant coatings are not easy to peel off when working at a high deformation rate, and still maintain a strong thermal resistance.

6 REFERENCES

► Chen X. Study on damage behavior and failure mechanism of rollers. 2018.

► Lv Z J, Qin Q, Jiang B, et al. Comparative study on the mechanical mechanism of confined concrete supporting arches in underground engineering. Plos One, 2018, 13(2).

► Zhou N, Wang J X, Tang S Z, et al. Study on the failure and energy absorption mechanism of multilayer explosively welded plates impacted by spherical fragments. Mechanics of Composite Materials, 2018, 53(8):809-820.

► Iqbal J, Dai F C, Hong M, et al. Failure mechanism and stability analysis of an active landslide in the xiangjiaba reservoir area, southwest china. Journal of earth sciences, 2018.

► Peng J Y, Li Y H, Zhang F P, et al. Failure process and mechanism of sandstone under combined equal biaxial static compression and impact loading. Strain, 2018, 54.

► Chen Y, Liu F H, Nong Y Q, et al. Clinical efficacy and mechanism of growth hormone action in patients experiencing repeat implantation failure. Canadian Journal of Physiology & Pharmacology, 2018, 96(1).

► Singh S, Valenciajaime I, Pavlic O, et al. Elastic, mechanical, and thermodynamic properties of bi-sb binaries: effect of spin-orbit coupling. 2018, 97(5).

► Mei Y, Liu W, Brugger J, et al. The dissociation mechanism and thermodynamic properties of hcl(aq) in hydrothermal fluids (to 700 °c, 60 kbar) by ab initio molecular dynamics simulations. 2018, 226:84-106.

► Jadhav S, Schoiswohl M, Buchmayr B. Applications of finite element simulation in the development of advanced sheet metal forming processes. Bhm Berg Und Hüttenmännische Monatshefte, 2018, 163(2):109-118.

► Liu J, Wang A, Gao H, et al. Transition of failure mode in hot stamping of aa6082 tailor welded blanks. Journal of Materials Processing Technology, 2018.

► Mo L, Zhu X, Tao Z, et al. Temperature rise calculation of a flux-switching permanent-magnet double-rotor machine using electromagnetic-thermal coupling analysis. 2018, 54(3):1-4.