Investigation on Ultra-high Temperature Forging Process Based on DEFORM-3D Simulation

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Research Article

Keywords: the ultra-high temperature demoulding, DEFORM-3D, the temperature fields, the equivalent stress, the equivalent strain, hot cracking

Posted Date: February 12th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-196059/v1>

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Abstract

Green manufacturing and forming technology is becoming increasingly important in modern industry. In this study, a new forging technology with the ultra-high temperature demoulding is introduced, in which conventional reheating process could be avoided. The DEFORM-3D software simulated the forging process and the temperature fields were obtained. The traditional forging process was simulated when the initial forging temperature was 1220°C. The highest temperature of the ingot in the new forging technology was about 200°C higher than that of the traditional forging process. We cut the ingot longitudinally along the centerline. Nine points on the axis of the cutting plane and nine points on the radial direction were selected. The equivalent stress and the equivalent strain of these points were compared respectively under the two forging processes by using the particle tracking method. The variation laws of the equivalent stress and the equivalent strain with the reduction were obtained. According to the variation laws, the typical points which were easy to crack under two different forging processes were found. Based on the flow stress-strain curve calculated by the software JMatPro®, the new forging technology could avoid hot cracking.

Introduction

The forgings produced by the traditional forging process have some defects, such as solidification segregation, shrinkage cavity, porosity, cracks and so on. With the development of the high performance of the large equipment, it is necessary to produce high quality heavy forgings. So the forging process innovation has attracted the attention of the industry.

In the steel rolling field, the soft reduction process [1-2] with liquid core has been widely used. In this process, the pressure is applied to the solidification end of the continuous casting billet, which helps improve the quality of iron and steel products. Kawasaki Water Island plant [3] in Japan has adopted the forging and rolling process for the slab with the liquid core at the end of the liquid-phase cavity. When a specific section of the continuous casting slab passes through the deformation zone, it has to pass through the arc hammer several times. A large reduction can be decomposed into multiple small reductions, which are not only conducive to breaking the columnar crystal and accelerating the solidification, but also reducing the slab stress. Liquid pool control system (LPCS) is used in the fractional thermally stimulated current (FTSC) technique[4-6]. The length of the liquid cavity of the casting slab is measured and controlled by the steel grades, the slab section, the temperature of the tundish, the casting speed, the cooling speed of the mold, and other process parameters. During the casting process, the system always tracks the solidification endpoint of the cast slab so that the reduction endpoint is maintained at the end of the liquid cavity with a suitable solid phase ratio. The reduced amount of each sector is reasonably distributed, so as to achieve the best effect of reducing segregation and central porosity. The process improves the quality of the slab, realizing true dynamic soft reduction with liquid core.

Previous scholars have studied the soft reduction with liquid core in the rolling process, which is very mature in the industrial field, but there is little research on the forging process with liquid core. It is very necessary to change the traditional production process of heavy forgings and study the preparation technology of heavy forgings with uniform composition and structure. Wang Kaikun et al. [7-8] proposed and implemented a green short-flow forging process in engineering, namely forging process with liquid core since 2014. This new process follows the technological process "smelting-casting-high temperature demoulding-forging". Compared with the traditional forging process, repeated heating is avoided and it is also helpful in saving energy. In this short process, the casting alloy ingot is demoulded at ultra-high temperature. The highest temperature of the ingot in the new forging technology was about 200-300°C higher than the initial forging temperature of the traditional forging process. Then the ingot is sent to the forging press for upsetting and drawing.

In this paper, the DEFORM-3D software[9-12] is used to simulate the ultra-high temperature forging process and the traditional forging process. The typical points which are easy to crack under two different forging processes are found. Under the condition of the specific temperature and the specific strain rate, we propose a way to judge whether the crack is produced or not.

1. Establishment Of The Model

1.1 Material

The material used in this paper is Assab 718[13-15] which is a Swedish grade steel. The steel has good machinability, wear resistance and uniform hardness distribution. It also has good polishing performance and its processing technology is simple. Assab 718 is widely used to make large size and high-grade plastic mold parts. The chemical composition is shown in Table1. Fig.1(a-d) show Assab 718's properties related to the deformation.

Table1 Chemical compositions of ASSAB 718 (wt.%)

C	Si	Mn	P	S	Cr	Mo	Ni	Fe
0.34	0.3	1.4	0.01	0.008	1.9	0.33	1	balanced

1.2 Finite element modelling

The ingot is octagonal [16-18] and the specific dimensions are shown in Table 2. The steel ingot slope is 3.93% with the height to diameter ratio 1.5. The solidus temperature and the liquidus temperature of the Assab 718 are 1423°C and 1487°C. The casting temperature is 1530°C. After casting, the ingot is demoulded at high temperature and then it is sent to the press for forging with higher temperature in the

core. According to the solidification law of the ingot, the temperature increase gradually from the bottom to the top. The other ingot is cooled with mold for more than 10 hours after casting and then it is demoulded. The ingot is heated in the soaking furnace until the internal temperature and the external temperature reach 1220 °C. Then the ingot is sent to the press for forging.

Table 2 Ingot dimension parameters

Ingot type	Regular octagonal Plum blossom ingot
Riser height /mm	300
Ingot body height /mm	1400
Length of large head side/mm	1025
Length of small head side/mm	915

The upper anvil materials and the lower anvil for forging are both H13 die steel with length 1600 mm × width 1600 mm × height 200 mm, as shown in Fig.2(a). The initial temperature is 300°C. The ingot surface is a free surface which exchanges heat with the environment, the upper anvil and the lower anvil. The ingot is regarded as an ideal rigid plastic body in the forging process, so the volume change caused by the elastic deformation is not considered. The reduction speed of the upper anvil is 30 mm·s⁻¹ and the reduction amount is 600 mm whose reduction rate is 32%, as shown in Fig.2(b-c). The ingot is forged with the riser and the riser is sawed off after the finished product is produced.

2. Comparison Of The Equivalent Stress And The Equivalent Strain

2.1 Comparison of the equivalent stress and the equivalent strain of longitudinal nodes

In the simulation results of the DEFORM-3D software, the ingot is longitudinally cut along the section passing through the central axis of the ingot. The temperature increases gradually from the bottom to the top of the ingot. Nine points P₁, P₂, P₃, P₄, P₅, P₆, P₇, P₈ and P₉ in different temperature regions are selected on the longitudinal centerline of the cutting plane, as shown in Fig.3. The equivalent stress and the equivalent strain of the nine points in the traditional forging process are extracted according to the above method on the basis of the simulation results. The variation curves of the equivalent stress and the equivalent strain with the reduction are shown in Fig.4 and Fig.5.

Fig. 4 (a)-(b) show the change of the equivalent stress with the reduction and it can be seen from that the equivalent stresses of P₁, P₂ and P₃ decrease slightly at the beginning of the deformation in the ultra-high temperature forging process. The equivalent stresses of the other points are on the rise. The slopes of the curves of P₇, P₈ and P₉ at the bottom are the largest. Those indicate that the equivalent stresses change significantly with the increase of the reduction. The equivalent stresses of P₇, P₈ and P₉ in the ultra-high

temperature forging process increase with the increase of the reduction while the equivalent stresses of P_7 , P_8 and P_9 in the traditional forging process decrease with the increase of the reduction. At the beginning of the deformation, the equivalent stresses of the other points increase rapidly in the traditional forging process. When the reduction reaches a critical value, the equivalent stress reaches the maximum value. And then it decreases slowly and tends to a stable value in the traditional forging process. When the deformation is completed, the equivalent stress at P_8 at the bottom in the ultra-high temperature forging process is the largest. While in the traditional forging process, the equivalent stress at P_4 in the middle is the largest.

It can be seen from Fig. 5 (a) that the equivalent strains of P_2 and P_3 are the largest in the ultra-high temperature forging process. The equivalent strain of P_9 at the nozzle position is the lowest and the value is close to zero. It can be seen from Fig. 5 (b) that the equivalent strains of P_1 at the riser and P_9 at the nozzle are the smallest in the traditional forging process. The equivalent strains of P_7 and P_8 in the ingot are always higher than those of the other 7 points, which indicate that the points 500-700 mm away from the bottom has the largest cumulative deformation in the whole deformation process.

2.2 Comparison of the equivalent stress and the equivalent strain of transverse nodes

The ingot is longitudinally sectioned along the section through the central axis of the ingot. P_1 , P_2 and P_3 are selected along the radial direction at the riser position. P_4 , P_5 and P_6 are selected along the radial direction at the middle position. P_7 , P_8 and P_9 are selected at the nozzle position, as shown in Fig. 6. The equivalent stresses and the equivalent strains of the nine points in the deformation are extracted in the ultra-high temperature forging process. According to the above method, the equivalent stresses and the equivalent strains of the nine points at the same position are extracted on the basis of the simulation results in the traditional forging process. The curves of the equivalent stresses and the equivalent strains changing with the reduction are obtained as shown in Fig. 7 and Fig. 8 respectively.

It can be seen from Fig.7 (a)-(b) that when the reduction is less than 500 mm, the equivalent stress of each point in the ultra-high temperature forging process is smaller than that in the traditional forging process. In the whole deformation process, the equivalent stresses of P_7 , P_8 and P_9 points at the nozzle position increase with the increase of the reduction while the equivalent stresses of P_7 , P_8 and P_9 at the nozzle position in the traditional forging process decrease with the increase of the reduction.

It can be seen from Fig.8 (a) that the equivalent strain distribution is obvious in the ultra-high temperature forging process. The points P_1 , P_2 , and P_3 near the riser have the largest equivalent strains and the highest temperatures. The points P_7 , P_8 , and P_9 at the nozzle have the smallest equivalent strains and the temperatures of P_7 , P_8 and P_9 are the lowest. Compared with the equivalent strains of the points in the radial direction of the steel ingot, the equivalent strains of the points located on the surface are always

higher than those of the core points. It can be seen from Fig. 8 (b) that the equivalent strain of P_9 at the nozzle is the largest and that of P_7 at the nozzle is the smallest in the traditional forging process.

3 Analysis Of The Hot Crack

3.1 Mechanism of hot cracking

The formation of hot cracking we discussed in this paper is determined by two factors: the temperature and the strain rate.

1) The yield strength decreases with the increase of the temperature. There are a lot of dislocations in the material and a large number of them gather to form the Cottrell atmosphere. On the micro-level, the yield strength is the force that dislocations overcome the pinning of the Cottrell atmosphere's surroundings. With the increase of the temperature, the pinning effect of the Cottrell atmosphere on the dislocations is weakened and the force required for the dislocations' slip is also reduced. On the macro level, it is manifested as a decrease in the yield strength of the material;

2) The yield strength increases with the strain rates. The time responded to the strains decreases when the strain rates rise. It causes work hardening and more external stress will be applied to the whole material for completing the whole forming process. On the macro level, it is manifested as an increase in the yield strength of the material.

3.2 Points prone to cracks

According to the mechanism of cracks' formation mentioned above, cracks are easy to occur in the high temperature region or in the low strain rate region. From the simulation results of DEFORM-3D, P_1 is located in the area with the highest temperature as shown in Fig. 9 (a) and P_2 is located in the area with the lowest equivalent strain rates from 4.32×10^{-5} to 0.053, as shown in Fig. 9 (b). Two representative characteristic points P_1 and P_2 are selected on the deformed body after the ultra-high temperature forging process. If P_1 and P_2 do not crack during the upsetting [19-21] and the whole workpiece will not crack. In the traditional forging process, the temperature differences in the deforming body after the upsetting are small, as shown in Fig. 9 (c). The differences of the equivalent strain rate are also very small with the lowest equivalent strain rates from 6.33×10^{-4} to 0.0358, as shown in Fig. 9 (d).

When the temperature and the equivalent strain rate are known, the maximum principal stress can evaluate the possibility of cracks in the forging process. The workpiece is prone to cracks in the place where the maximum principal stress is large. So in the traditional forging process only one representative point P_1 is selected, as shown in Fig. 9 (c). P_1 is located in the area with the highest maximum principal stress. In the same way, if no cracks occur at P_1 , the entire workpiece will not crack.

3.3 Hot cracking prediction method

In the ultra-high temperature forging process, the temperature is 1430°C and the equivalent strain is 0.42 at P_1 where the strain rate is 0.02 s^{-1} . According to the calculation results of JMatPro®, the maximum stress Assab 718 can bear is 9.55 MPa, as shown in Fig. 10 (a). It is larger than the maximum principal stress of 9.27 MPa obtained by the finite element simulation, so there is no crack at P_1 . When the temperature is 1200°C at P_2 , the deformation strain rate is 0.001 s^{-1} and the equivalent strain is 0.02. According to the JMatPro®, the maximum stress the material can bear is 16.25 MPa, as shown in Fig. 10 (b). It is larger than the maximum principal stress of 15.14 MPa obtained by the finite element simulation, so there is no crack at P_2 . In the traditional forging process, the temperature of P_1 is 1200°C and the equivalent strain becomes 0.02 where the strain rate is 0.01 s^{-1} . According to JMatPro®, the maximum stress that Assab 718 plastic mold steel can bear is 17.41 MPa, as shown in Fig. 10 (c). It is less than the maximum principal stress of 21 MPa obtained by the finite element simulation. Therefore it is easy to crack at P_1 during the traditional forging process. In the production process, the reduction speed should be reasonably controlled to increase the strain rate.

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4 Conclusion

In this paper, the ultra-high temperature forging process is simulated by DEFORM-3D software. Compared with the traditional forging process, the following conclusions are obtained:

1) In the process of the ultra-high temperature forging, the equivalent stresses of the points near the bottom change greatly along with the central axis. The points in the highest temperature have the largest equivalent strains. Compared with the nine radial points of the ingot, the equivalent stress at the nozzle position increases with the increase of the reduction. The equivalent strain at the surface points is always higher than that at the core points;

2) We have found the positions where cracks are easy to appear in the forging process. We analysed the temperature and the equivalent strain rate of the selected typical points. The analysis process combines with the maximum principal stress of the material. The maximum stress that can be withstood under the specific strain is obtained by the simulation software JMatPro® of the material performance. By comparing with the maximum principal stress in the forging process, it is concluded that the ultra-high temperature forging process is not easy to produce hot cracking.

Declarations

-Ethical Approval and Consent to Participate

Not applicable.

-Consent to Publish

- that the work described has not been published before (except in the form of an abstract or as part of a published lecture, review, or thesis).
- that it is not under consideration for publication elsewhere;
- that its publication has been approved by all co-authors, if any;
- that its publication has been approved (tacitly or explicitly) by the responsible authorities at the institution where the work is carried out.

-Authors Contributions

Kaikun Wang contributed to the conception of the study;

Yongqiang Wu performed the experiment, contributed significantly to analysis and manuscript preparation, performed the data analyses and wrote the manuscript;

-Funding

This work was financially supported by the National Key Research and Development Program of China (2017YFB0701803).

-Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

-Availability of data and materials

The data used to support the findings of this study are included within the article.

Acknowledgements

The authors would like to sincerely thank the National Key Research and Development Program of China (2017YFB0701803) for the financial support.

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Figures

Figure 1

Assab 718's properties (a) Young's modulus, (b) Poisson's ratio, (c) Shear modulus, (d) Bulk modulus.

Figure 2

Finite element model (a) before forging, (b) after forging with the new technology, (c) after forging with the traditional technology

Figure 3

Locations of sampling points

Figure 4

The equivalent stresses of nine longitudinal points (a) the ultra-high temperature forging, (b) the traditional forging

Figure 5

The equivalent strains of nine longitudinal points (a) the ultra-high temperature forging, (b) the traditional forging

Figure 6

Locations of sampling points

Figure 7

The equivalent stresses of nine radial points (a) the ultra-high temperature forging, (b) the traditional forging

Figure 8

The equivalent strains of nine radial points (a) the ultra-high temperature forging, (b) the traditional forging

Figure 9

Locations of sampling points (a) the distribution of the temperature in the ultra-high temperature forging, (b) the distribution of the equivalent strain rate in the ultra-high temperature forging, (c) the distribution of the temperature in the traditional forging, (d) the distribution of the equivalent strain rate in the traditional forging

Figure 10

Flow stress-strain curves in JMatPro®