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Paper:

One Action Press Forming of Helix Bevel Gear by Using Multi-Cylinder Press and Die Heating System

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In the case of a complex shaped helix bevel gear, the forging of complete gear tips is very difficult to achieve. In almost all cases, tooth profile is finished by cutting machine from simple shaped forged parts, therefore requiring considerable machining time and cost. However, there are many approaches to forging. Forging is mainly classified as hot and cold forging, and uses a single motion press. In the case of hot forging takeoff of products from die is difficult by the cooling shrinkage from die and accuracy of products is lower level than cold forging. In addition, in the case of cold forging, a complicated shape is difficult to achieve based on the lack of ductility of the materials. To realize a helix bevel gear using a single forging operation, we applied a tool heating system and three-axis forging press. The tool heating system is applied to prevent a temperature decrease in the material by contact between the tool and forging material during the forging process. Further, to optimize the forging direction and timing, we used a three-axis forging press. We confirmed good forging capability of this special forging process, as well as the high precision of the forged parts. Moreover, through the thermo-mechanical control of steel and the tool temperature, the forged parts showed good mechanical properties, such as high hardness.

Keywords: forge, helix bevel gear, heated tools, multi cylinder press

1. Introduction

The forging process is classified into cold forging and hot forging according to the temperature of the work applied. Cold forging work pieces are forged at room temperature. The features of cold forging are high precision and high productivity, but are restricted to a simple shape.

Hot forging work pieces are forged at high temperature, usually at about 1,150°C. The main feature of hot forging is the formability, and thus a complex shape can be achieved; however, the precision is not high and a draft is required. As a result, a lengthy machining time is needed after forging.

To improve the precision, warm forging has recently been applied. Warm forging uses a work piece temperature of 800–900°C [1–4].

In all forging processes, the materials and die temperatures differ. For example, in the case of hot forging, the work pieces are heated up to 1,150°C, and the die temperature is about 150°C, using a preheated gas burner. In the case of warm forging, the work piece temperature is about 900°C, although the die temperature is the same as with hot forging. In cold forging, the work pieces and die are not preheated, and the die is actually heated up to 150°C through plastic deformation and friction between the die and the work pieces.

On the contrary, isothermal forging is used for titanium and magnesium alloys and an ideal forging process. As a result, this process is able to minimize the shrinking of the work pieces caused by their temperature difference between the die. Work pieces are not cooled by contact with a cold die. Thus, the isothermal forging process allows a high precision of complicated shapes. In material of a commercial production die is steel alloy, the heat resistance temperature of which is about 500°C, and the strength of the die degrades by overheating. Thus, it is desirable for the die temperature to be below 500°C.

Based on this situation, we developed a new forging process called a semi isothermal forging system (SIFS). SIFS is composed of a die heating system and work pieces at a lower working temperature compared with hot and warm forging. By controlling the die and temperature of the work pieces, an improvement in mechanical properties is realized. In other words, SIFS is a mechanical heat treatment process.

A die heating system heated to over 400°C is not popular. We developed a new die heating system for SIFS.

We then tried to forge a complex shaped helix bevel gear using SIFS and confirmed the formability and an improvement of the mechanical properties.

2. Die Heating System for SIFS

For contact between the die and heater in our heating system, a heater is located above and below each die where a severe pressure load is applied. Usually, a breakdown or deformation of the heater or its holder is caused

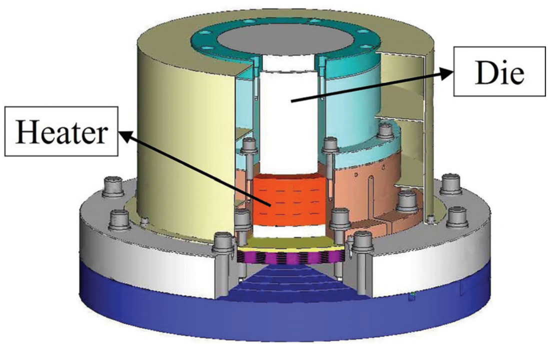

Fig. 1. Structure of the die heating system.

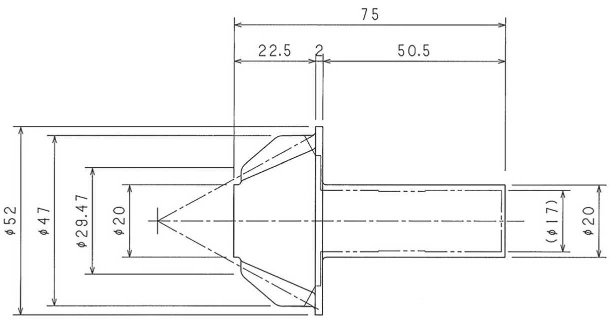

Fig. 2. Principle dimensions of helix bevel gear.

Table 1. Principle specifications of helix bevel gear.

Tooth profile	Gleason
Module	4.1
Number of tooth	11
Pressure angle	22.5°
Helix angle	35°
Pitch circle	45.1 mm

from this load.

To resolve this problem, the structure of the die heating system and the layout of the heater are as follows:

(1) The temperature of heater should be controlled below the maximum operating temperature of the material, including the heater holder and other nearby parts.

(2) Maximize the heat capacity of all heater holder by uniforming the temperature of heater holder.

(3) Designing heater holders that have pressure relief structure to press working.

As a result, we developed a die heating system with a maximum heating temperature of up to 500°C (**Fig. 1**). In this die heating system, the upper die has a diameter ϕ of 180 mm and height of 176 mm. The lower die has a diameter ϕ of 180 mm and a height of 150 mm. In this system, heaters are not in contact with the die directly, and thus, exchanging the die is quite easy and the heaters are not damaged during a die exchange operation.

3. Multi-Cylinder Presses

Multi-cylinder presses are not popular for forging. The contact period between the die and work piece is longer than a single cylinder press. In the case of hot and warm forging, as the work piece is cooled by the die, the forgeability decreases. As a result, the cost of the press equipment increases.

In contrast, a multi-cylinder press shows good performance for the forging of a complicated shape and high precision parts.

We try to use a multi-cylinder press with a die heating system for an expansion of the forgeability [5–14].

4. Experimental Procedure

4.1. Experimental Material

An alloy made up of Fe – 0.35 wt% C, 0.27 wt% Si, 0.73 wt% Mn, 0.016 wt% P, 0.013 wt% S, 0.09 wt% Cu, 0.06 wt% Ni, 1.01 wt% Cr, 0.17 wt% Mo, was used for these experiments, and was selected because chromium molybdenum steel is commonly used for gear forging.

The size of each work piece has a diameter ϕ of 19 mm and a length of 144 mm. The work pieces are heated to a certain temperature through induction heating.

4.2. Target Shape for Forging

The target shape is a helix bevel gear, and its tooth profile is a Gleason type (**Fig. 2**). The module number is 4.1, the pressure angle is 22.5°, the torsion angle is 35°, the diameter of the pitch circle ϕ is 45.10 mm, and eleven teeth are used (**Table 1**).

4.3. Forging Procedure

4.3.1. Forging Press

The forging press is equipped with six hydraulic cylinders (**Fig. 3**). The main and upper and lower cylinders are set vertically, and three additional cylinders can be placed at a free position and direction. All of the hydraulic cylinders are computer controlled, and the data on the position, speed, and pressure can be acquired at 0.01 s intervals.

4.3.2. Forging Process

We used three vertically placed hydraulic cylinders. Usually the cylinders do not move together. However, in this study, the cylinders do move together and their start and stop times are controlled.

As the first main cylinder starts to move, the upper and lower cylinders start to move as well (**Fig. 4**).

The first stage is the upsetting of the rod. As the three cylinders start to close the die, the upper and lower cylinders become faster than the main cylinder.

Fig. 3. Appearance of hydraulic press with six cylinders.

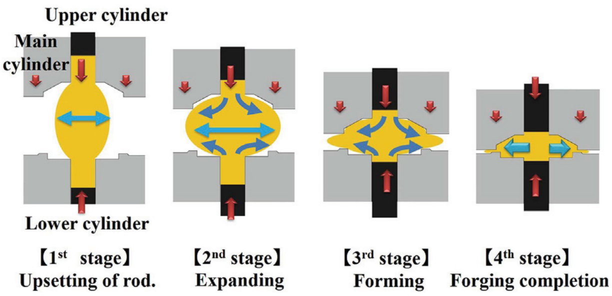

Fig. 4. Image of forging process by three-cylinder press.

The second stage of the forging process is expansion. The upper and lower cylinders are the supplying materials. At this time, buckling is prevented through the materials being gradually pushed out from the die.

In addition, the lateral material supply is assisted through the upper and lower cylinders.

The third stage is the formation. The material flow is restricted in the outer periphery of the die, and materials are filled the tooth mark part with.

The fourth stage is the completion of the forging. The material becomes completely pervasive through the pressures of the upper and lower cylinders within a die.

The principal dimensions of tools are shown in **Fig. 5**. The tools are made of high-speed tool steel and tool steel.

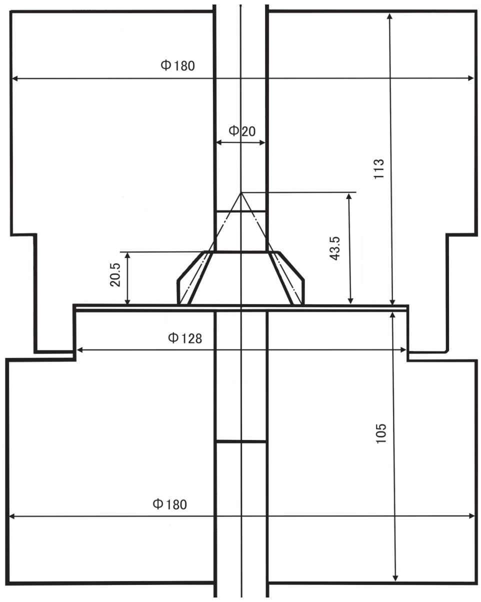

Fig. 5. Principal dimensions of the tools.

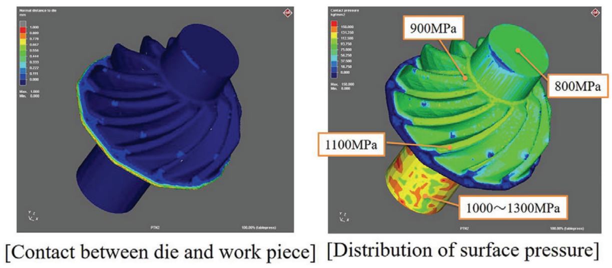

Fig. 6. Results of simulation for helix bevel gear forging.

Table 2. Condition of press cylinders.

	Load [KN]	Speed [mm/s]
Main cylinder	2,000	30
Upper cylinder	300	110
Lower cylinder	400	80

5. Experimental Results

5.1. Simulation of Forging

Using the simulation software SIMFACT, we selected any forging condition (**Fig. 6**).

Based on the results of the simulation, we selected each cylinder speed, the timing of the start of the cylinder, and the cylinder load.

We then attempted to find the tuning details of the forging press conditions. We fixed the speed of the main cylinder, and set the speed of the upper cylinder to 40–120 mm/s. We then set the speed of the lower cylinder from 30–130 mm/s.

Finally, we found the best conditions under which the die becomes filled with the material, where each cylinder moves at a different speed and load, as shown in **Table 2**.

Using this condition, we can obtain a fully shaped helix bevel gear. The temperature of the work piece is 800°C and the die temperature is 400°C. The surface condition of the gear is better than in a usual hot or warm forging process (**Fig. 7**).

The measurement data on a forging press are shown in **Fig. 8**. The main cylinder starts to move first, and the upper and lower cylinders start about 2 s after the main cylinder. In addition, the pressure load of each cylinder is maintained for 5 s.

After loading, all cylinders are released concurrently.

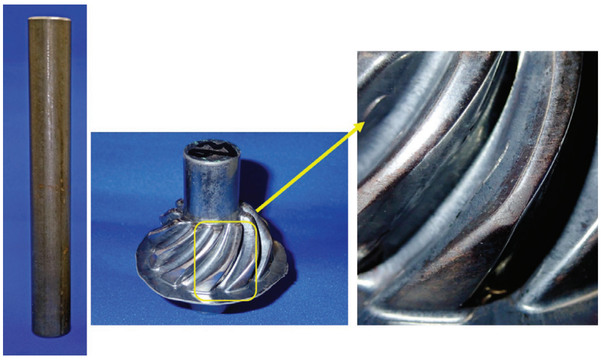

Fig. 7. Image of helix bevel gear forging product.

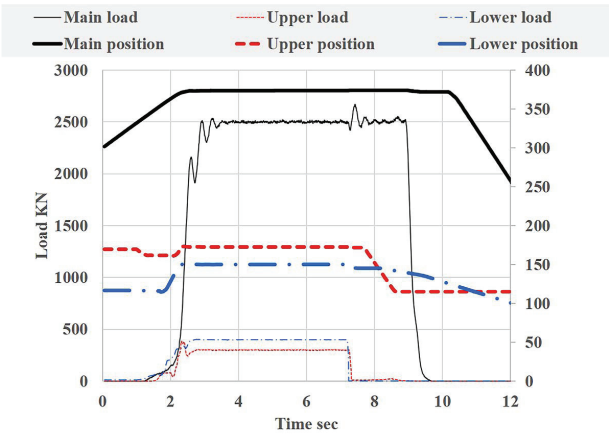

Fig. 8. Diagram of hydraulic press.

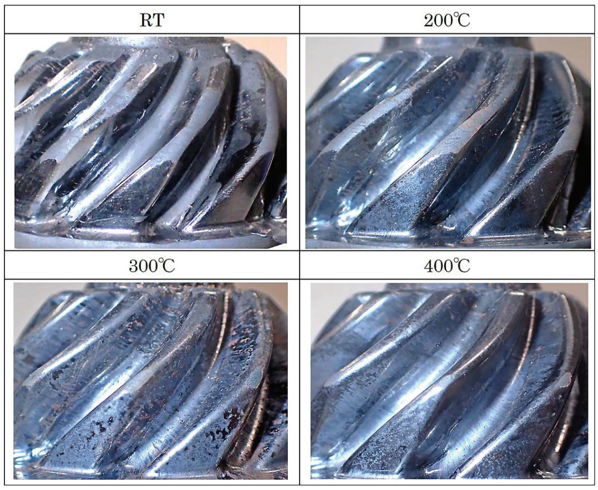

Fig. 9. Influence of die temperature for formability.

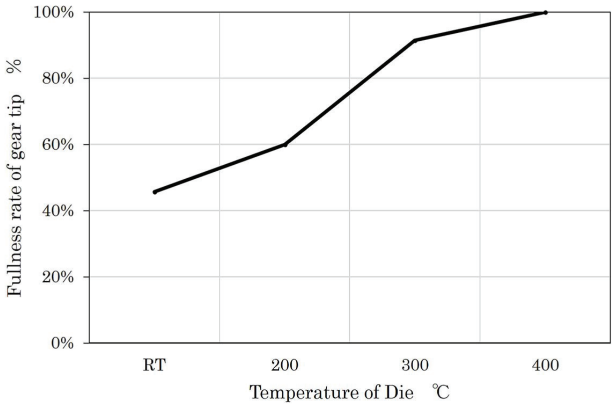

Fig. 10. Relationship between fullness rate of gear tip and die temperature.

5.2. Influence of Die Temperature for Formability

As **Fig. 9** shows, the formability depends on the die temperature.

For the die temperatures, room temperature (RT), 200°C, 300°C, and 400°C were selected. The temperature of the work piece was 800°C.

At room temperature, the tips of gear were not filled with the tooth material. The non-contacted area of the die and the material were concentrated at the tips of the gear teeth. According to the increase in temperature, the die formability is improved and the non-contact areas of gear tips decrease. At 300°C, the formability is better than at 200°C, and forged part approximately formed as an objective shape. However, the tips of the gear teeth were not perfectly filled with the material.

When the die temperature reached 400°C, we could obtain an objective shaped forging part.

From this result, we could confirm that the die heating is effective for forgeability. The material heated at 800°C was cooled by contact with the die. Depending on the die heating, the cooling degree reduced, and the forgeability increased.

To estimate the formability, we defined the length of the tooth ridgeline as the "fullness rate of the gear tip." Under the condition of a full formation at 400°C, the die temperature reached 100%.

Figure 10 shows the influence of the die temperature for the fullness rate of the gear tip.

The fullness rate of the gear tip was improved as the die temperature increased.

Regarding the die release characteristics used in this study, parts were taken out of the die quite easily after forging because the temperature difference between the die and work pieces were minimized by the die heating. When the parts were removed from the die, the work piece temperature was below 600°C. As a result, the heat shrinkage of the work piece was minimized, allowing the work piece to be removed quite easily after forging. This result is very important for practical mass production.

5.3. Precision of Forging Gear Product

We measured the processing accuracy of the gear forged at 400°C using a three-dimensional coordinate measuring machine (Carl Zeiss PRISMO navigator) and GEAR PRO measurement software (**Fig. 11**).

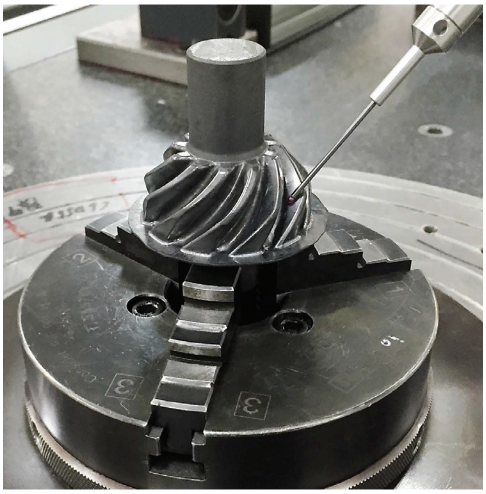

Fig. 11. Appearance of gear shaped measurement.

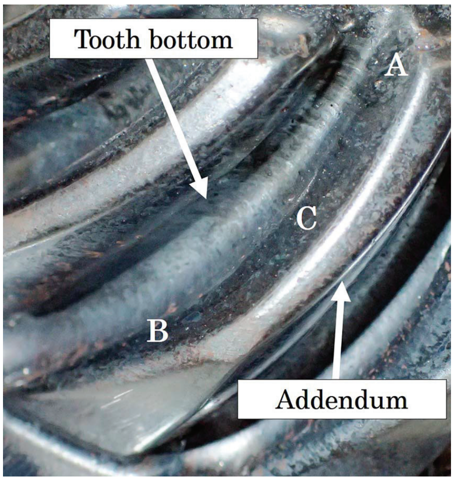

Fig. 12. Measurement area.

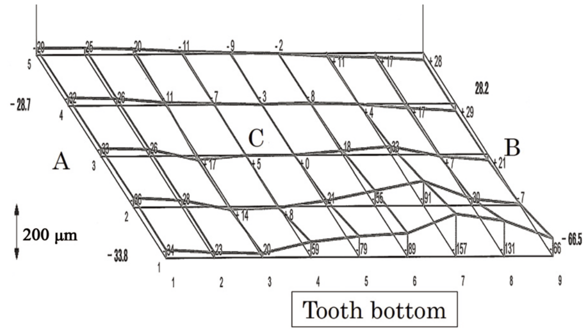

Fig. 13. Measurement result of gear.

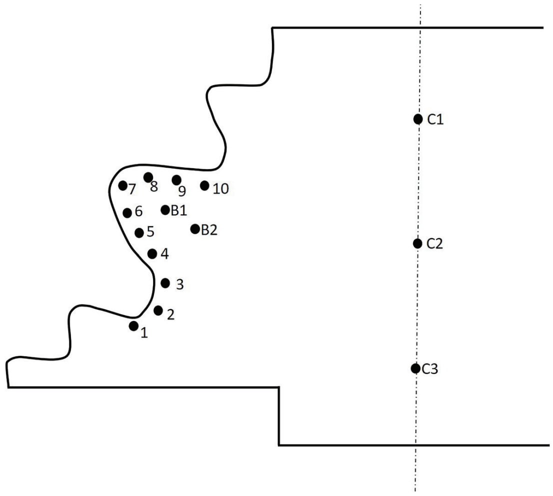

Fig. 14. Hardness measurement points.

We measured the shape position from areas A to B, as shown in **Fig. 12**. The reference point of this measurement is C, and we checked the difference between the tool and forged gear shape.

The difference in the shape position between the tool and forged gear showed a tendency to increase at position B, particularly at the tooth bottom (**Fig. 13**).

We estimated this difference based on the elastic deformation of the tools because position B received higher pressure than position A, and the tools did not have sufficient rigidity to prevent elastic deformation of the tools when applying the forging pressure.

5.4. Influence of Work Piece Temperature for Hardness Distribution of Forging Parts

Using a Vickers hardness measurement, we measured the longitudinal cross section of the forged parts.

The die temperature was constant at 400°C. The measurement was conducted three times at the same points, and the mean value was applied.

We selected the measurement points of the hardness in three areas. Initially, the surface points were located 1 mm from inside the tooth surface and number 1 through 10. This area is very important to the gear properties. The next area is the center of the tooth, which is indicated by B1 and B2. Finally, the center area of the gear body on the gear axis is shown as C1 through C3 (**Fig. 14**).

For the hardness of the tooth tip material, a temperature of 700°C showed low hardness and large dispersion. Only the bottom of the tooth showed high hardness at $HV = 350$. However, the tip of the tooth showed low hardness at about $HV = 250$. These data indicated that the bottom of the tooth deformed with the large amount of strain and the long slip length between the die and work piece (**Fig. 15**).

Based on the effective temperature, the temperature of the material will be sufficiently high to reach a γ-phase, and was quenched by cooling through contact with the die.

At 900°C, the hardness showed a high value of about $HV = 330$, and distribution of hardness was uniform. Based on these data, the temperature of the work piece reached the γ domain.

At 800°C, the hardness of the tooth tip appeared to be harder than at 900°C, and was as uniform.

The quenching temperature of the sample material is

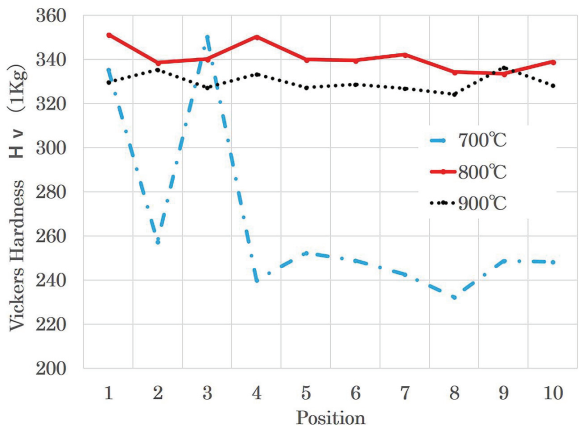

Fig. 15. Hardness distribution of tooth edge area.

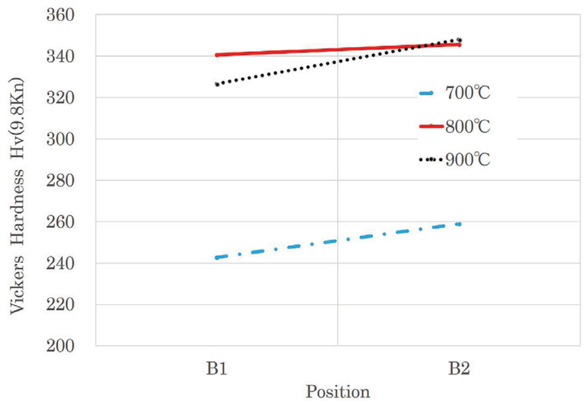

Fig. 16. Hardness distribution of tooth center area.

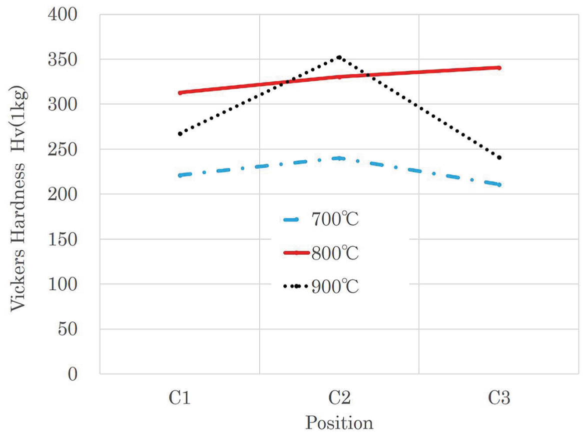

Fig. 17. Hardness distribution of center of forging part.

from 830°C to 880°C. A work piece temperature of 800°C or below appeared to be insufficient.

Through the heat generation caused by the plastic deformation and friction heat, the material of the work piece at 800°C was heated up to the quench temperature, and the hardness appeared to be high.

Normally, at a higher temperature, the hardness of steel after quenching appeared to be higher. However, at 800°C, the heating hardness appeared to be higher than under 900°C heating.

This result may be in accord with the grain refinement at 800°C. The grain size depends on the working temperature based on the Zener-Hollomon parameter, which is a well-known equation between the grain size and working temperature.

The fine grain of the metal alloy shows a higher strength than the coarse grain based on the Hall-Petch relationship, which is a well-known equation between the grain size and proven stress.

We considered the reasons for the high degree of hardness at 800°C to be the grain refinement by plastic deformation and the quenching through work piece heating [15–20].

The hardness of the tooth center showed approximately the same tendency as the tooth tip. Position B2 showed higher hardness than position B1, which was estimated to be because the plastic deformation strain of position B2 is larger than that of position B1 (**Fig. 16**).

The hardness at the center of the forging part showed a different tendency as the tooth tip because the center does not receive severe strain during the forging process (**Fig. 17**).

C1 and C3 were located near a non-deformed area, similar to a rod. Thus, such areas were not heated by the plastic deformation as tooth.

In this area, C2 showed a high hardness. This position received severe compression deformation from the upper and lower sides. We estimate that the hardness was higher than that of C1 and C3.

6. Discussion

Three-axis press forging is a suitable forging process for complex shapes of the metal parts. One-axis forging is only a limited plastic deformation process. In contrast, the use of more than two cylinders can achieve a changeable cylinder speed and free timing. The tip of a tooth is the most difficult forging area after or during the closing of the main cylinder through control of the upper and lower cylinders, which we can control and optimize in the direction of plastic deformation. We control a three-cylinder press because we can forge a complexly shaped helix bevel gear.

However, the accuracy of the forged gear parts is insufficient because tools near position B receive high pressure, and the tools do not have sufficient rigidity to prevent elastic deformation based on the forging pressure.

Using a die heating system, reducing the temperature difference keeps its remarks minimum. The deformability depends on the work piece temperature. However, the mechanical properties are decreased as the temperature increases. Using a die heating system, the forging temperature is easily controlled, and the mechanical properties are improved.

7. Summary and Conclusion

Through the combination of a three-cylinder press forging and die heating system, we confirmed that the SIFS is effective with regard to high-precision and complicated shape forging.

1) Through the combination of a three-cylinder press and die heating system, we can forge a helix-shaped bevel gear using a single press operation.

2) The accuracy of the forged gear parts has been insufficient because the tools do not have proper rigidity to prevent elastic deformation of the tools based on the forging pressure.

3) Through the control of the work pieces and die temperature, we can improve the hardness and its distribution.

4) We confirmed that the semi-SIFS is effective for the forging of complex and high-strength steel parts.

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Membership in Academic Societies:
- Japan Society of Mechanical Engineers (JSME)
- Japan Society for Precision Engineering (JSPE)
- Quality Engineering Society (QES)