Study on cracks and process improvement for case hardened gear shaft straightening

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Abstract  Deformation of the gear shaft in transmission is inevitable after case hardened heat treatment. Straightening is the normal way to ensure the straightness requirement. During the straightening process, cracks often appear and result in scrapped parts. Based on the situation of high rejection rate of straightening crack of the internal input shaft of a dual-clutch automobile transmission, this paper makes an in-depth analyses of the pressure straightening process theory, the crack generation mechanism, the working process of the automatic straightening machine and the crack detection system, etc., and establishes the relationship between the ram increment, the total displacement and the crack rate during multi-step progressive straightening, proposes a way to quickly judge the straightening performance of the parts. Finally, after optimizing the pressure position by finite element analysis, optimizing the straightening procedure by adjusting ram increment and adopting vector straightening method, optimizing the parts martial properties by heat treatment improvement, the straightening crack rate of internal input shaft was reduced from 1.95 % to 0.14 %.

1. Introduction

Transmission is a set of transfer device in automobile which used to coordinate the engine speed and the actual driving speed of the wheels, mainly used to transmit the speed and torque that are generated by engine. Gear shaft is one of the key components for transmitting torque and speed in automotive transmission. During the production of the gear shafts, parts will be distorted after heat treatment, and it need to be straightened to meet the straightness requirements. For the straightening of gear shafts, pressure straightening is generally used.

Pressure straightening is known as three-point reverse bending straightening. The main process is to hinge the two ends of the part firstly, and then apply a reverse force on the parts until reverse deformation occurs. After the reverse force removes, a part of the workpiece spring back, while the other part has permanently deformed. If the permanent deformation reaches the initial deflection, the workpiece finish straightening. Straightening crack is prone to occurs during straightening and result in scrap. This paper focuses on reducing the straightening crack in the internal input shaft in a dual-clutch transmission, which is as high as 1.95 %. By studying the gear shaft straightening process and the mechanism of crack generation and implementing a series of measures to reduce the straightening crack rate. Fig. 1 shows the internal input shaft picture. Fig. 2 shows the straightening crack.

At present, research on pressure straightening theory and technology which based on elasto-plastic theory are faced mainly two basic problems: the combination of punch-anvil and the displacement of ram. Among them, the study of the ram displacement is the most critical and the most difficult issue, and it is also the hot pot of current straightening theoretical research. Stelson et al. [1-3] did a lot of pioneering work on the intelligent control of V-bending in the 1980s. Starting from the load-displacement curve, he developed an adaptive control method that can effectively control the displacement of punch in real time according to the theoretical...
model derived from elastoplastic mechanics. Talukder and Singh [4] conducted a more systematic elastoplastic mechan- 
ical analysis of the pressure straightening reverse bending process which laid a good theoretical foundation for pressure 
straightening technology. Katoh et al. [5, 6] studied the real-
time control of seamless steel pipe straightening, it’s not only 
introduced the hydraulic system and detection system of 
straightening equipment in detail, but also introduced the use 
of empirical formulas to predict the springback of parts based on 
the elastoplastic theory. Murata et al. [7] found that parameters 
such as bending radius, springback and stress distribution 
during workpiece straightening were significantly affected by 
the work hardening of the material through finite element nu-
merical simulation. Eggertsen and Mattiasson [8] based on this 
research, in order to more accurately predict the springback of 
pressure straightening, through the modeling process of re-
verse bending straightening, the springback of different mate-
rial strengthening models were analyzed and compared. 
Megharbel et al. [9] calculated the residual stress and spring-
back during the straightening process of the parts through the 
Al-Qureshi algorithm, with certain reliability. Schleinzer and 
Fischer [10, 11] studied the stress superposition and Bausch-
inger effect during the straightening process, and proposed the 
influence of punch displacement on the straightening process. 
Kim and Chung [12, 13] conducted a more in-depth study on 
the multi-step straightening control system, and introduced a 
fuzzy self-learning algorithm in the straightening process to 
compensate for the increment of the punch during straighten-
ing process. In addition, it also elaborates the influence of the 
straightening punch point on other straightening points, and 
takes this effect as an important consideration for the selection 
of punches when the shaft is in the elastic deformation stage. 
Zhai [14] based on the multi-step straightening process to classify the 
bending deformation on the basis of elastoplastic deformation, 
and adopted different punch-anvil combination straightening 
strategies for each type of bending. Through a lot of experi-
ments, the work load-deflection equation is optimized, and the 
punch control based on deformation is effectively achieved. 
Zhao [15] used finite element analysis to study the mechanical 
properties of the three-point pressure straightening, and the 
analysis results can be an effective reference for the selection 
of punch points during pressure straightening.

Nowadays, straightening theory has been studied in depth, 
but it needs to be improved in practical application, such as 
less research on the straightening process for transmission 
gear shafts which case hardened by heat treatment in the lit-
erature. For this type of parts straightening, not only should pay 
attention to how to straighten the bent parts effectively, but also 
need consider how to reduce the straightening crack rate, cur-
cently lack of systematic improvement studies to meet the 
needs of mass production [16].

2. Gear shaft pressure straightening theory and straightening crack mechanism analysis

2.1 Process of gear shaft straightening

For the alignment of gear shaft, pressure straightening is 
generally used. Pressure straightening is a method which 
make use of the parts to produce elastoplastic deformation 
after receiving a certain pressure to straighten the parts. Cur-
rently, the straightening pressure is not easy to be accurately 
controlled in real time, while the straightening displacement can 
be accurately controlled in real time by the precision electro-
hydraulic servo system, so most of the automatic straightening 
machines implement precise straightening by controlling the 
ram displacement. Since the shape and structure of the gear 
shaft in the transmission and the initial stress distribution are 
relatively complicated, and after surface hardening heat treat-
ment, the material properties of the parts between surface 
components and the core components are quite different. 
Therefore, there is no mature algorithm to guide the straighten-
ing practice. At present, the gear shafts straightening mainly 
adopt multi-step progressive straightening method [17].

When the stress exceeds elastic yield limit, it goes to elasto-
plastic deformation stage. Fig. 3 shows the elastoplastic zone 
division of the gear shaft after load pressure. Zone 1 is the 
elastoplastic compression zone, zone 2 and zone 4 are rigidly 
rotated, zone 3 is the elastic deformation stage, and zone 5 is 
the elastoplastic stretching zone.

From the calculation of the mechanics formula, it can be seen 
that when the shaft is in the elastic deformation stage, the 
maximum stress of the part is on the surface below the pres-
sure point, and it can be calculated as:

$$\sigma_{\text{max}} = \frac{32M}{\pi D^2}$$  \hspace{1cm} \text{(1)}$$

In the elastoplastic deformation stage, based on the elastic 
linear strengthening model, the maximum stress value on the 
surface of the part can be calculated as:
\[ \sigma_{\text{max}} = \sigma_s + \lambda \sigma_c \left( \frac{1}{\xi} - 1 \right) \] (2)

where \( \lambda = E_p/E \), \( E_p \) is the strengthened elastic modulus, \( E \) is the initial elastic modulus, \( \sigma_c \) is the yield strength, and \( \xi \) is the elastic yield ratio, \( \xi = \frac{H}{D} \).

2.2 Parts bending forms

The bending of the gear shaft after heat treatment mainly includes the following forms as Fig. 4 shows.

The output shaft of the dual-clutch transmission is stubby and generally present single-bending type after heat treatment, while the slender internal input shaft has a variety of deformation forms such as single-bending type, and multiple bending type. The single-bending type conforms to the classic three-point reverse bending straightening model is relatively easy to be straighten, but unreasonable straightening process may also make single-bending into multiple bending, while straightening of multiple bending parts are relatively difficult in straightening [18, 19], that's the reason why the straightening crack rate of the inner input shaft is higher than that of the output shaft.

2.3 Mechanism of straightening crack

According to the theory of straightening, the parts appear straightening cracks because the maximum stress exceeds the tensile strength. The material used in the gear shafts is generally low-carbon alloy steel. The hardness after heat treatment normally not higher than 50 HRC, showing good plastic deformation ability. In order to make the gear shaft have high fatigue strength, good wear resistance, while have good toughness at the same time, the gear shaft is usually subjected to surface carburizing heat treatment. After the heat treatment, although the surface properties of the parts have been significantly hardened after heat treatment, the toughness has also been significantly reduced. Fig. 5 shows the straightening crack after case hardened heat treatment. It can be seen that the crack originates from the carburized hardened layer on the surface of the part, which extends from the surface to the inside, and featured as brittle.

2.4 Discussion on improvement of straightening crack

For the straightening of carburized gear shaft parts, because of the surface hardened layer has high tensile strength and relatively brittle properties, while the base component performs plastic toughness, so the process mainly reduces the bending of the parts through the elastoplastic deformation of the base component. In order to avoid straightening cracks, it is necessary to complete the elastoplastic deformation of the base component before the maximum stress on the surface reaches the tensile strength. By consulting relevant information and studying the straightening process, it can be conclude that straightening crack improvements can be made mainly from the following aspects:

(1) Improvement of punch-anvil combination

For most of the straightening machines used to straighten the gear shaft of the transmission, the anvils are generally fixed on the workbench, so the straightening is generally performed by changing the position of the pressure point. According to the analysis of the pressure straightening mechanical model, it can be seen that even if the pressure point is not at the maximum bending position, the maximum deflection is also near the middle of two anvils. Therefore, when the stress concentration facts such as grooves and oil holes are just at the maximum bending point, it is possible to reduce the deflection at the stress concentration area by pressing other positions.

(2) Improvement of straightening program

The improvement of the straightening procedure include ram increments improvement and straightening strategy improvement. For the selection of the ram increments, although due to the complex structure of the gear shaft and the different properties of the surface components and core components after heat treatment, there are currently no mature algorithms and empirical formulas to learn from, but generally based on the consideration of straightening cracks, the increments cannot be too large, and based on the consideration of work hardening and cycle time, the increments cannot be too small. For the
selection of the straightening strategy, data collection and analysis should be carried out on the straightening process.

The pressure points that are prone to straightening cracks should be reduced the number of straightening times, and the bending be reduced by other pressure point. In addition, the current advanced automatic straightening machine already has vector straightening function. On the one hand, it can avoid the influence of stress concentration factors such as oil holes by accurately selecting the straightening angle, on the other hand, it can be straightened by multiple angles which will decompose the large stress into several small stresses to reduce the maximum stress value during straightening [20].

(3) Improvement “straightening property” of parts

The “straightening property” refers to the ability of the bend parts to be straightened without generating straightening crack. Because of the surface hardened part need to complete the elastoplastic deformation before the maximum stress of surface component reaches the tensile strength, therefore, if the base component of the part has good plasticity and low yield strength, it will help prevent the occurrence of straightening cracks. Usually heat treatment is an important way to improve the straightening performance of parts.

3. Straightening process of gear shaft of automatic straightening machine

Automatic straightening machine has been widely used in the field of gear shaft straightening. The internal input shaft straightening of the dual-clutch transmission be studied in this paper is carried out on the PAS/30 automatic straightening machine from Galdabini Company. The straightening machine is a device that integrates automatic loading and unloading, parts identification, center hole cleaning, and online crack detection.

3.1 Working theory of PAS/30 automatic straightening machine

Fig. 6 shows the curvature measurement system model of PAS/30 automatic straightening machine. Sensors no. 1 and no. 5 are the reference, the values measured by the three sensors, respectively, no. 2, no. 3 and no. 4 are used to obtain the deflection and the spatial azimuth angle of the three measurement points A, B and C by least squares.

The crack detection system based on acoustic emission can not only realize online detection, but also be efficient and accurate that have been widely used in the field of straightening [21]. PAS/30 type automatic straightening machine adopts the CIS0.1 online crack detect system which produced by QASS company to judge whether there are straightening cracks during the straightening process.

3.2 Straightening program

As shown in Fig. 7, due to the various deformation forms of the inner input shaft after heat treatment, the straightening adopts three anvils with three punch points. P1, P2 and P3 represent three punch position, S1, S2, and S3 represent three anvils position. When P1 is working, P1, S1 and S2 form a three-point reverse bending straightening model; when P5 is working, P5, S2 and S3 form a three-point reverse bending straightening model; when P3 is working, S2 will automatically move down, out of contact with the shaft, so P3, S1 and S2 form a three-point reverse straightening model. M0, M1, M3, M5, and M7 represent five sensors position. Among them, M0 and M7 are reference sensors, cooperate with M1, M3, and M5 to measure the bending and azimuth angle. Finally, after the parts finish straightening, deflections of M1, M3 and M5 all need ≤ 0.03 mm. According to status survey, it can be easy found that straightening cracks of internal input shaft are all generated at P1, and the crack positions are all on groove D.

Fig. 8 shows the current straightening process of internal input shaft. According to the magnitude of the deflection at different pressure points, given an initial displacement for ram, and the displacement is progressive with the number of straightening increases, usually with the deflection decreases and increments decreases accordingly as Fig. 9 shows until the program segment is finished. This method makes the ram gradually progresses and by controlling the increment, so that the surface stress is gradually increased. The advantage of this method is not only avoids the situation of over bending at the first time, but also effectively captures the maximum stress of the part between the yield strength and tensile strength so that can realize both part be straightened and crack avoidance.

4. Methods of straightening crack improvement

4.1 Finite element analysis and improvement of the position of the pressure point

In view of the powerful analysis and simulation functions of finite element simulation software, more and more research uses finite element analysis to guide straightening practice and achieves good results [22-25]. By simulating the stress state during the straightening process, it can provide strong support for the selection of pressure position during straightening. This
paper uses ANSYS finite element analysis software to analyze the straightening process of internal input shaft, aiming at finding the best pressure position.

4.1.1 3D model establishment

Fig. 10 shows the 3D model of internal input shaft straightening. Due to the gears, splines and top hole top are not the impact factor, so it’s simplified when drawing.

As shown in Fig. 11, since the straightening cracks are all generated on groove D during straight on P1. Therefore, the simulation process focused on P1 process. P1, S1, S2 form a three-point reverse bending straightening.

4.1.2 Analysis of stress magnitude at different punch points

Fig. 12 shows according to the structure of the internal input shaft, there are three position options for the P1. Beside the current pressure position ②, there are other two pressure positions ① and ③.

Table 1 shows the maximum stress value for different P1 position when loading the same force. It can be seen that when the P1 at the position ①, the maximum stress point is on groove D, which is consistent with actual crack position. When the P1 point is at the position ①, the stress is the smallest, so according to finite element simulation, it can be concluded that the position ① is the best straight point for the P1 point.

| P1 position | ① | ② | ③ |
|-------------|----|----|----|
| Maximum tensile stress value (MPa) | 236 | 399 | 426 |
| Maximum tensile stress position | Groove C | Groove D | Groove D |
4.1.3 Experimental verification

From the finite element simulation results of P1 point, it is known that the point \( \textcircled{1} \) is the best position of P1. So P1 was changed to position \( \textcircled{1} \). A total of 2700 pieces in 15 loads were continuously straightened for verification. Finally a total of 38 rack pieces. The crack rate dropped from 1.95 % to 1.41 %, and the crack position moved from groove D to groove C, the crack position is consistent with the results of finite element simulation.

4.2 Straightening process analysis and improvement

4.2.1 Increments analysis and improvement

Fig. 14 shows the effectiveness of increment magnitude during straightening process. It can be seen that when initial deflection of the three parts are approximately the same, the retained deflection value after straightening is less than 30 \( \mu m \). Three increments of 30 \( \mu m \), 60 \( \mu m \), and 90 \( \mu m \) were selected for the test. When the increment is 30 \( \mu m \), a total 18 times be straightened and the total increment is 540 \( \mu m \). When the increment is 60 \( \mu m \), a total 8 times be straightened and the total increment is 480 \( \mu m \). When the increment is 90 \( \mu m \), only 4 times be straightened and the total increment is 360 \( \mu m \). None of the three parts generate cracks. Therefore, it can be conducted that in the range of no straightening cracks, increasing the increment can not only reduce the number of straightening time, but also reduce the total increment of ram. In addition, the slopes of the three curves all show a trend from large to small, which also reflects work hardening during the straightening process, it will leads to increase in the yield strength, so that leads to a decrease in deflection under the same increment.

Since all cracks are generated when straightening at P1 position, and due to the influence of work hardening straightening process, the ideal straightening process should reduce the number of straightening times as much as possible under the condition that the increments should not be too large to cause straightening cracks, this paper will reduce P1 straightening time from two aspect as follow:

(1) Decreasing the deflection of P1 by decreasing the deflection of P3. Since the distance between the P3 and the anvil is the longest, the bending moment that under the same load is the largest, so the parts are more prone to plastic deformation. From the actual straightening result, it can be seen that there is no straightening crack on this pressure position. Therefore, if the spatial azimuth at points P1 and P3 are at the same, the deflection value of point P1 can be reduced by straightening point P3. so that the straightening times will be reduced when straightening P1.

(2) Increase ram increment. From the relationship between increment and the retained deflection which is shown in Fig. 14, it can be concluded that an appropriate increase of the ram increment can not only reduce the number of straightening times, but also reduce the total increment of ram, thereby reducing the total displacements and finally reducing maximum stress on the part surface. Fig. 15 shows the comparison before and after the improvement of the incremental-deflection curve of P1. P3 and P5 are also increased the increments to some extent.

4.2.2 Vector straightening

According to the discussion on the straightening crack before, vector straightening method can reduce the maximum stress of P3. Since the distance between the P3 and the anvil is the longest, the bending moment that under the same load is the largest, so the parts are more prone to plastic deformation. From the actual straightening result, it can be seen that there is no straightening crack on this pressure position. Therefore, if the spatial azimuth at points P1 and P3 are at the same, the deflection value of point P1 can be reduced by straightening point P3. so that the straightening times will be reduced when straightening P1.

(2) Increase ram increment. From the relationship between increment and the retained deflection which is shown in Fig. 14, it can be concluded that an appropriate increase of the ram increment can not only reduce the number of straightening times, but also reduce the total increment of ram, thereby reducing the total displacements and finally reducing maximum stress on the part surface. Fig. 15 shows the comparison before and after the improvement of the incremental-deflection curve of P1. P3 and P5 are also increased the increments to some extent.
by decomposition. Therefore, P1 adopt vector straightening method. As is shown in Fig. 16, the conventional signal point pressure is divided into three points during straightening, the angle between the two points is set to 30°, and the punch sequence is P1, P2, P3.

4.2.3 Experimental verification
A total of 1800 pieces were continuously straightened for verification and a total of 19 crack pieces. Crack rate dropped from 1.41% to 1.05%. When tracking and observing the straightening, it was found that the decrease of the deflection of P3 obviously drive to decrease of the deflection of the P1. Straightening times on P1 is significantly reduced. In addition, due to the increase in the increment, the average cycle time is reduced from 48 s to 44 s.

4.3 Material properties analysis and improvement of heat treatment process
According to the elastoplastic theory of part straightening, the mechanical properties of the material is one of the key factors for generating straightening cracks. Heat treatment is an indispensable step in the production process of gear shafts. It is also the most important process that affects the mechanical properties. A reasonable heat treatment process plays a very important role in improving the mechanical properties of parts materials.

4.3.1 Heat treatment process
Vacuum carburizing gas quenching continuous furnace from France ECM company is used for the internal input shaft. The furnace adopts pulse carburizing, the carburizing pressure is 10-15 mbar, the carburizing medium is acetylene, and the gas quenching medium is nitrogen.

The reaction formula of acetylene decomposition by Wei [26] is:

\[ C_2H_2 \rightarrow 2[\text{C}] + \text{H}_2 + 53.5\text{kcal}. \] (3)

Fig. 17 shows the heat treatment process of internal input shaft, it can be seen that the preheating temperature is 380 °C and the time is 84 min; the heating temperature is 970 °C and total time in the heating cell is 135 min; the gas quenching pressure is 13 bar and time is 5 min; the tempering temperature is 170 °C and time is 168 min; the air cooling time is 36 min.

4.3.2 Heat treatment deformation state
Heat treatment deformation mainly contributed by the inconsistent structure transformation during heat treatment process and the different stresses generated by each component. It’s the inherent characteristic of heat treatment. Although gas quenching has smaller deformation than ordinary oil quenching, it still needs to be straightened to meet the requirement of deflection.

Quenching cooling rate is the important factor that directly affect the structure transformation and stress. It’s the key parameters that affect the heat treatment deformation. For the gas quenched part, the gas quenching pressure determines the cooling rate. As shown in Fig. 18, three loads (labeled A, B, and C, respectively) are extracted for showing the deflection distribution. It can be seen that although the distribution of deflections is fluctuations to some extent, it’s normally distributed in general.

4.3.3 Improvement of heat treatment
According to the theory of microstructure transformation during heat treatment and the influence of material properties on straightening, reducing the core hardness can effectively reduce the yield strength and yield-tensile ratio, so that provide more space for plastic deformation during straightening, thereby helping to reduce the generation of straightening cracks. Therefore, it is an ideal choice to control the core hardness in lower limit range. Table 2 shows the quality inspect results when gas quenching pressure is reduced from original 13 bar to 7 bar.

According to the table, it can be seen that with the decrease of the gas quenching pressure, the core hardness of the part is significantly reduced, and the other items have little change, when pressure is 9 bar, the core hardness is lower limit range, and the other quality inspection results are within the qualified range, so 9 bar can be selected as the gas quenching pressure parameter.

This paper compares 3 loads (540 pieces) of the deflection distribution of the parts before and after the gas quenching pressure is changed. As Fig. 19 shows, the deflection of the parts are significantly reduced, the average value of deflection...
decreased from 118.2 μm at 13 bar to 92.6 μm at 9 bar.

It can be concluded from Fig. 19 that reducing the gas quenching pressure can not only reduce the core hardness, but also reduce the deflection, thereby reducing the possibility of straightening cracks advanced.

Due to the reduction of core hardness and yield-tensile ratio, the plasticity and toughness of the parts are enhanced, theoretically it can improve “straighten properties”. As shown in Table 3, this paper made a comparison of “straightening property” before and after the heat treatment process is improved by the way of progressively increasing the ram until generate crack on P1.

It can be seen from Table 3 that after the gas quenching pressure decreased from 13 bar to 9 bar, due to the decrease of the core hardness and the enhancement of the plasticity and toughness of the parts, the displacement and increment of the ram can be greatly increased. Fig. 20 shows the comparison of P1 increment after heat treatment is improved, it can be seen that the increments has been greatly increased again.

### 4.3.4 Experimental verification

A total of 3600 pieces were continuously tracked after

| Items           | Requirement | Quenching pressure |
|-----------------|-------------|--------------------|
|                 | 7 bar       | 9 bar   | 11 bar  | 13 bar  |
| Surface hardness (HRC) | 59-63 | 59.6  | 59.8  | 60.5  | 61   |
| Core hardness (HV)      | 370-500 |        | 344    |       | 379   | 408   | 424   |
| Case depth (mm)         | 0.55-0.75 | 0.59  | 0.61  | 0.63  | 0.65  |

| Microstructure        | Requirement | Quenching pressure |
|-----------------------|-------------|--------------------|
| Martensitic grade 1-4 | 4           | 4                 | 4      | 4      |
| Retained austenitic grade 1-4 | 3 | 3 | 3 | 3 |
| Carbide grade 1-3     | 1           | 1                 | 1      | 1      |
| Ferritic grade 1-3    | 1           | 1                 | 1      | 1      |

| Yield-tensile ratio (tested by tensile sample) | Requirement | Quenching pressure |
|------------------------------------------------|-------------|--------------------|
|                                                  | /           | 0.726              | 0.768   | 0.795  | 0.802  |

Table 2. Quality inspect result of the internal input shaft.

| Quenching pressure (bar) | Initial deflection (μm) | Ram displacements (μm) | Retain deflection (μm) | Core hardness (HV) |
|-------------------------|-------------------------|------------------------|------------------------|--------------------|
| 13 bar                  | 265                     | 300                    | 198                    | 462                |
|                         |                         | 400                    | 104                    |                    |
|                         |                         | 500                    | Crack                  |                    |
| 9 bar                   | 267                     | 300                    | 145                    | 385                |
|                         |                         | 400                    | 75                     |                    |
|                         |                         | 500                    | 44                     |                    |
|                         |                         | 600                    | 33                     |                    |
|                         |                         | 700                    | 27                     |                    |
|                         |                         | 800                    | Crack                  |                    |

Table 3. Comparison of "straightening property" before and after heat quenching pressure improvement.

Fig. 19. Deflection distribution of parts under different gas quenching pressures.

Fig. 20. Incremental comparison of P1 before and after improvement.
quenching pressure changes from 13 bar to 9 bar, finally 5 crack pieces. Crack rate dropped from 1.05 % to 0.14 %. When observation the straightening process after improvement, it was found that the straightening performance of the parts has been significantly improved. In addition, due to the large increase in the increment, the straightening process was significantly accelerated, so the average cycle time was reduced from 44 s to 35 s.

4.4 Discussion

As shown in Fig. 21, after improving press position, straightening program and heat treatment process, straightening crack rate has been significantly reduced from 1.95 % to 0.14 %. Furthermore, the cycle time also has been reduced from 48 s to 35 s, thereby the production capacity has been greatly improved.

5. Conclusion

This study was initiated based on the high scrap rate of straightening crack. After the study of the pressure straightening process and the mechanism of cracks, three experimental methods supported by a finite element analysis are proposed to find best press position, straightening program optimization and heat treatment adjustment to improve material properties. After implementation of all three proposal, crack rate has been significantly reduced. There are four mainly constructions concluded as following:

1) For case hardened gear shaft, press straightening process mainly reduces the bending of the parts through the elasto-plastic deformation of the base component. In order to avoid straightening cracks, it is necessary to complete the elasto-plastic deformation of the base component before the maximum stress on the surface reaches the tensile strength.

2) The position of the pressure point has an important influence on the occurrence of straightening cracks, finite element analysis can effectively find the best pressure point position.

3) Multi-step progressive straightening is an effective way to reduce rack, but need attach great importance to the impact of increments, small increment will cause crack due to work hardening after too times punching while big increments will leads to excessive surface stress and cause cracks.

4) Core hardness can be used as an index to quickly judge the straightening performance of the parts, while gas quenching pressure is the key parameter that determines the core hardness if parts adopt vacuum heat treatment and gas quenching. Lowering the gas quenching pressure can effectively reduce the core hardness, thereby reducing the yield strength and yield-tensile ratio which can significantly reduce the straightening crack rate.

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