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Investigation of Effective Parameters on Annealing and Hot Spotting Processes for Straightening of Bent Turbine Rotors

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Abstract**—**The most severe damage of the turbine rotor is its distortion. The rotor straightening process must lead, at the first stage, to removal of the stresses from the material by annealing and next, to straightening of the plastic distortion without leaving any stress by hot spotting. The straightening method does not produce stress accumulations and the heating technique, developed specifically for solid forged rotors and disks, enables to avoid local overheating and structural changes in the material. This process also does not leave stresses in the shaft material. An experimental study of hot spotting is carried out on a large turbine rotor and some of the most important effective parameters that must be considered on annealing and hot spotting processes are investigated in this paper.

Keywords**—**Annealing, Hot Spotting, Effective Parameter, Rotor

I. Introduction

TYPICAL inlet temperature for HIP turbine elements is 540°C (1000°F) or more. Therefore, an HIP rotor operates within a temperature range that makes problems such as temper embrittlement, creep, thermal fatigue, corrosion, local distortions and so on, during its service [1]–[2]. A shaft that is straight at room temperature may bend when running at full load, especially if there is an uneven heating effect [3]. Bending causes vibration which may damage different parts of the machine, thus a large turbine rotor must run with low vibration levels during operation and when going through critical speeds [4]. Depending upon applied temperature and pressure, some damages occur gradually during long-term service. Additionally, some factors such as thermal shocks due to premature shut downs or trips, local rubbing and erosion due to inadequate installation and conditions can be categorized as susceptible factors to occurrence of some damages (asperities, cracking, etc) [5].

Straightening reduces vibration and bearing loads to improve performance and reliability, and bearing life is maximized. Also it allows performance to be improved by increasing operating speeds [3]. Through the years, different techniques have been developed for the straightening of bent members by the application of heat, hammer, or transverse force, singly or in combination [1].

Heat straightening method is based on restrained thermal expansion of metal causing as upsetting action. Holt et al, summarized the method as follows: “The method of applying heat must be such that the steel instead of expanding in length, will upset or expand inward. Also to make this method work well, there must be portions of the member that is cold and strong enough, and situated so to force the metal, to upset or expand inward when and where it is heated, unless some outside forces can be added’’ [6].

Fabricators have employed thermal stresses for dimensional modifications since the 1930’s [7]. These stresses have typically been used to camber and sweep steel bridge beams, but more recently to repair damaged bridge beams. Early research studies were focused on the thermal expansion and contraction properties of required steels and general procedures for applications [8]–[9].

The rotor straightening process must lead, at the first stage, to removal of the stresses from the material by annealing and next, to straightening of the plastic distortion without leaving any stress by hot spotting.

The annealing process involves upending the shaft so it hangs or stands vertically. This method allows uniform heating with a minimum use of floor space. A lathe is not needed. It does not allow interim measuring of rotor bowing correction [4]. This process causes to decrease the hardness in embrittled and damaged areas [10]. Annealing also is applied typically on rotors that have lesser amounts of bowing which need hardened areas softened by heat soaking at temperatures above the operating temperature. Blading is protected from excessive heating and therefore, it can typically be reused. Electric heating methods are applied [4].

The hot spotting method involves setting the rotor in a lathe or similar turning device. The rotor is turned when needed to measure shaft straightening progress with dial indicators. This method is typically used when shafts have high values of bowing and can also reduce excess hardness during heating cycles. Differential heating methods can be utilized to correct local bending [4]. The action of heat applied to straighten shafts is that the fibers surrounding the heated spot are placed in compression by the weight of the rotor, the compression due to expansion of the material diagonally opposite, and the resistance of the other fibers in the shaft. As the metal is heated, its compressive strength decreases so that ultimately

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the metal in the heated spot is given a permanent compression set. This makes the fibers on this side shorter and by tension they counterbalance tension stresses on the opposite side of the shaft, thereby straightening it [11].

The annealing and hot spotting methods typically utilize heat treat cycles to reduce shaft bowing and any excess hardness.

II. ANNEALING

Annealing is a generic term denoting a treatment that consists of heating to and holding at a suitable temperature followed by cooling at an appropriate rate, primarily for the softening of metallic materials. Heating is to be performed by means of electric resistance elements, as the temperature must not exceed permutation temperature. Stress relief annealing is used to achieve three substantial objectives:

1) Elimination of the stresses caused by distortion.
2) Homogenization of the rubbing points and reduction of its hardness.
3) Relieving the stresses induced by any thermal/mechanical processing (rubbing in this study) and ensure dimensional stability.

III. Effective parameters on annealing

The success of any annealing operation depends on the proper choice and control of the thermal cycle. Variables associated with tempering that affect microstructural and mechanical properties of tempered steel include:

1) Tempering temperature
2) Holding time
3) Heating and cooling rate
4) Composition of the steel, including carbon content, alloy content, and residual elements

A. Tempering Temperature

Variation of mechanical properties depends on microstructural changes due to essential thermal influences. In carbon steels containing small percentages of the common alloying elements, one distinguishes the following stages during tempering [12]:

1) Stage 1 (20 to 100 °C, or 70 to 212 °F). Short-range diffusion of carbon atoms to dislocations and martensite plate boundaries; formation of carbon clusters.

2) Stage 2 (100 to 200 °C, or 212 to 390 °F). Precipitation of transition carbides.

3) Stage 3 (200 to 350 °C, or 390 to 660 °F). Transformation of retained austenite to ferrite and cementite.

4) Stage 4 (250 to 700 °C, or 480 to 1290 °F). Formation of ferrite and cementite. Spheroidized carbides in a matrix of equiaxed ferrite grains comprises well-tempered steels, that is, tempered for long times at temperatures approaching 700 °C (1290 °F).

At higher temperature, the formation of more complex carbides takes place in steel in which strong carbide forming elements are present [13].

In steels alloyed with chromium, molybdenum, vanadium, or tungsten, formation of alloy carbides occurs in the temperature range 500 to 700 °C (930 to 1290 °F) [12].

During stage 1, the hardness increases slightly while during stage 2, 3, and 4 the hardness decreases.

The toughness of a steel increases with decreasing hardness. However, when certain impurities such as arsenic, phosphorus, antimony, and tin are present, a toughness minimum termed "temper embrittlement" may occur in the temperature range 350 to 600 °C (660 to 1100 °F) due to segregation of impurities to grain boundaries [12].

B. Holding Time

Since the diffusion of carbon and alloying elements are temperature and time dependent, therefore in the tempering cycle, the holding time is one of the most significant stages of annealing. Thus the process must be held at a definite temperature long enough to achieve desired changes properties (hardness is commonly used to evaluate the response of steels to tempering) [14].

The changes in hardness are approximately linear over a long range of time when the time is presented at a logarithmic scale. Rapid changes in hardness occur at the start of tempering. Less rapid, but still large, changes in hardness occur in subsequent times and finally smaller changes occur in the end times [13].

C. Heating and Cooling Rate

Heating rate can be a factor in annealing process. Rapid heating is usually desirable to help minimize carbide precipitation and to preserve the stored energy from cold or warm work required to provide recrystallization and/or grain growth. Thus rapid heating is usually required to prevention of grain growth.

Another significant factor that affects the properties of steels is cooling rate from the tempering temperature. Although tensile properties are not affected by cooling rate, toughness can be decreased if the steel is cooled slowly through the temperature range from 375 to 575 °C (705 to 1065 °F), especially in steels that contain carbide-forming elements. Elongation and reduction in area may be affected also. The slow cooling serves to promote partial precipitation of the solute carbon (that is, the dissolved carbon) from the ferrite phase and, in systems having rapid primary cooling, to prevent the formation of martensite in non-dual-phase steels [12].

However slow cooling, in still air or in the furnace, is recommended for all alloys to minimize distortion.

D. Composition of the Steel

The properties of the tempered steel are primarily determined by the size, shape, composition, and distribution of the carbides that form, with a relatively minor contribution from solid-solution hardening of the ferrite. These changes in microstructure usually decrease hardness, tensile strength, and yield strength but increase ductility and toughness.

Under certain conditions, hardness may remain unaffected by tempering or may even be increased as a result of it. For example, tempering hardened steel at very low tempering temperatures may cause no change in hardness but may achieve a desired increase in yield strength. Also, those alloy steels that contain one or more of the carbide-forming elements (chromium, molybdenum, vanadium, and tungsten) are capable of secondary hardening; that is, they may become somewhat harder as a result of tempering.

IV. Hot Spotting

The shaft bend should be mapped and the shaft placed horizontally with the convex side of the bend placed on top. The shaft should be supported so that the convex side of the bend will have the maximum possible compression stress available from the weight of the rotor. To straighten carbon steel shafts using the heating method, indicators should be placed on each side of the point to be heated. Heat should be quickly applied to a spot, using an oxyacetylene torch. Heat should be applied evenly and steadily. The indicators should be carefully watched until the bend in the shaft has about tripled its previous value. The shaft should then be evenly cooled and indicated. If the bend has been reduced, repeat the procedure until the shaft has been straightened. If, however, no progress has been made, increase the heat bend until the heated spot approaches a cherry red. The simulations help to prevent from local phase transformation and to control whole the process.

V. Effective Parameters on Hot Spotting

Numerical and experimental studies were carried out into the effects of various parameters on straightening process for the received bent turbine rotor. Investigation results showed that heat straightening method is sensitive to the following parameters:

1) Heating temperature
2) Heating time
3) Geometric size
4) Location of hot spot area
5) Insulation
6) Material property
7) Cooling method

A. Heating temperature

In order to achieve straightening effects, the local metal must exceed 600 °C, and will usually require a temperature of 700 °C or greater. Metal temperature are best checked using sensors which are held in contact with the rotor surface by mechanical means or, in the case of thermocouples only, are spot welded to the rotors using approved equipment and procedures. They are located as close as practicable to the heated zone [15].

The maximum temperature of the process is limited by inherent metallurgical properties of the rotor. Achieving a temperature in excess of 750 °C frequently causes local transformation to austenite, and upon heat removal quenching action, locally transforms this zone to martensite. Phase change to martensite has two undesirable effects. Firstly, it produces a volume dilation increase which counteracts the desired crushing effect produced by the combination of thermal expansion and yield point decrease. Secondly, it causes hardening and a very notch-brittle microstructure. Therefore hot spotting temperature must not exceeding 750 °C to avid failure and cracking [17].

B. Heating time

The heating time is one of the most effective factors which must be planned carefully. The long heating time increases the possibility of heat transfer to other areas which decreases thermal gradient and surrounded areas rigidity. Heat should be quickly applied to a spot using oxyacetylene torches to create the maximum straightening effect. Heat should be applied evenly and steadily. Optimization of heating time would be achieved by regulation of heat flux value and hot spot area. Simulation of heating process for a 0.08 m^2 hot spot area was carried out using MATLAB. Its results show that the required heating time for a temperature of 700 °C would increase by reduction of heat flux value (Fig. 1).

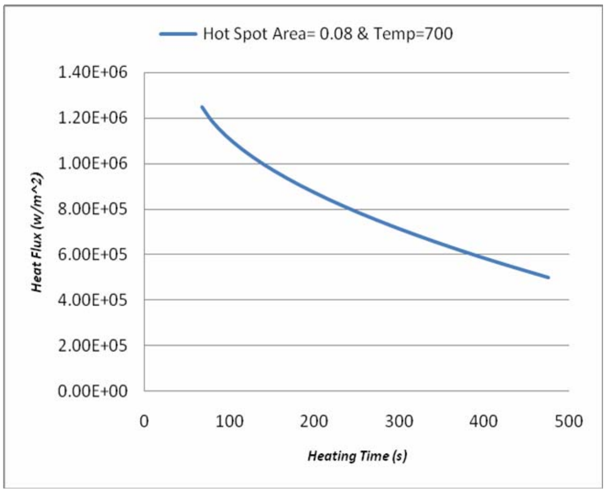


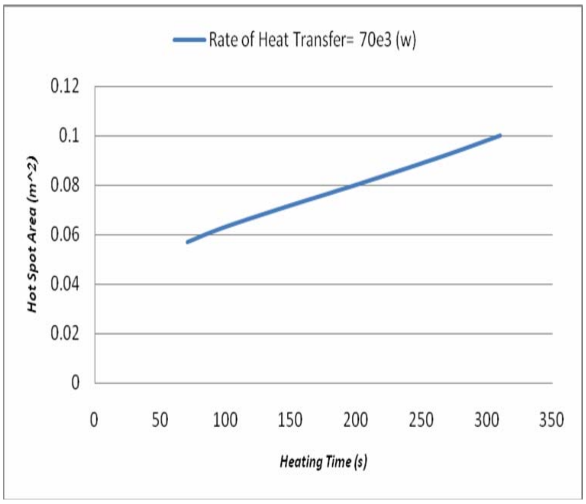
Fig. 1 Variation of heating time versus heat flux at a constant heating area

C. Geometric size

According to numerical results in Fig. 2 by reduction of heating area, shorter heating time is needed to achieve the required temperature using a constant rate of heat transfer.

D. Location of hot spot area

It is very important to find maximum bend point. The first thing to do, therefore, is to carefully indicate the shaft and map the bend or bends to determine exactly where they occur and their magnitude. The shaft should be supported so that the convex side of the bend will have the maximum possible compression stress available from the weight of the rotor. Thus the maximum point of bending is the best position for heating [11].In no event should the shaft be supported horizontally with the high spot on top and the support directly under the bend, since this will put tension stresses at the point to be heated, and heating will generally permanently increase the bend.



VFig. 2 Variation of heating time versus hot spot area at the same rate of heat transfer

E. Insulation

As the insulation causes significant restrain effects and increases thermal gradient around the heated area, it should be considered as an important parameter. Previous investigations indicated that, moisture insulation causes the maximum restraint effects around the hot spot area and also dry insulation is more effective than the state of without insulation [16].

F. Material property

There are some individual material properties such as thermal conductivity, thermal expansion coefficient, modules of elasticity, yield strength, poisson s ratio which are temperature dependent and other mechanical properties of the rotor material that must be considered as effective parameters on heating and cooling.

G. Cooling method

Several methods can be used for rotor cooling. The first method is that the rotor would not be cooled by the forced convection but rather, by natural convection and radiation. The second method is that rotor would be cooled by forced convection of ambient air, and the final method is that the dry compressed air during cooling would be used by forced convection method.

VI. Case Study

Annealing and hot spotting processes was done on a 325MW bent turbine rotor. After identification of the rotor damaged area, preliminary inspections such as visual inspection, crack test, chemical analysis, hardness and metallurgical tests were done. Results of initial inspections showed that the rotor suffer from rubbing.

According to previous discussions a proper annealing cycle was planned. Following detailed procedure was carried out before tempering:

1) The blades were removed on both sides of the straightening zone in order to be able to attach the heating elements.
2) Calcium carbonate solution was sprayed over the particular surface of rotor to prevent it from oxidizing and scaling, as shown in Fig. 3.

Fig. 3 Spraying calcium carbonate solution over the rotor surface

Fig. 4 Suspension of the Insulated rotor

3) Some thermocouples were held in contact with the rotor surface by spot weld in order to control the temperature, and they were located as close as practicable to the heated zone.
4) Resistance bulbs (heating elements) were set around the maximum point of bending to reach the ideal temperature and prevent from wasting heat.
5) Insulation of tempering area was done as a significant parameter of annealing process to achieve satisfactory temperature and maximum efficiency and prevent from thermal waste.
6) The rotor was suspended in order to decrease its gravity effects on distortion during the tempering (Fig. 4).

Annealing process then was implemented according to planned optimum tempering cycle while the rotor was vertically suspended.

When the rotor was completely cooled down to room temperature, visual inspection and crack test were carried out to detect probable damages due to annealing. Chemical analysis and hardening test was done to achieve mechanical and metallurgical condition of rotor material. In order to measure the remaining distortion, a radial run out test was performed. According to results of run out tests in Fig. 5 this process modified the rotor bending about 50%.

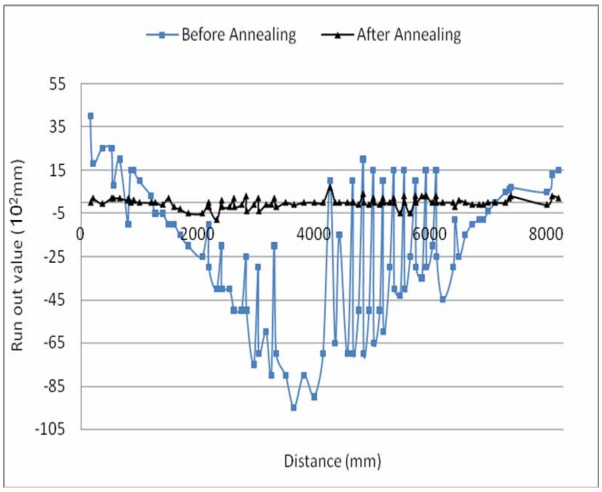


Fig. 5 Modification of rotor bending by annealing

After stress relieving process hot spotting was done on the rotor in accordance with received optimum conditions from the simulations. Figure 6 shows behavior of the rotor deflection during straightening process.

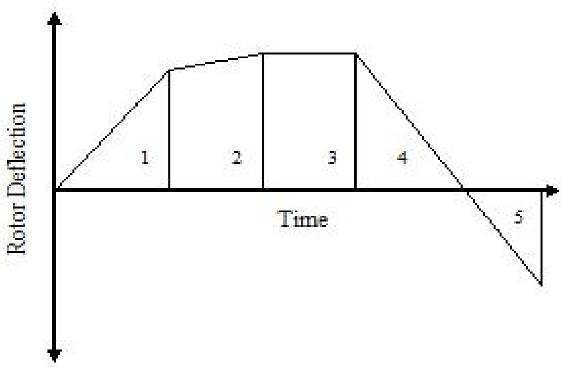


Fig. 6 Rotor deflection behavior during hot spotting

Zone 1: At the beginning of the hot spotting temperature rise and resistance of the fibers surrounding the heated area lead to expand it in free direction. Behavior of the rotor deflection in this scope is nearly linear. It is cleared that the nature of deformation in this zone is essentially elastic because resulted thermal stress is less than compressive yield stress.

Zone 2: As revealed, time increasing lead to propagate heat to other surrounding fibers, and the rotor deflection gradient gradually decreases. On the other hand as the metal is heated, its yield strength decreases so that produced thermal stresses start to overcome the metal strength which imply to threshold plastic deformation.

Zone 3: This zone is the main purpose to achieve required straightness and it occurred at the last moments of heating process. In fact by increasing temperature and thermal stresses, local plastic deformation occurs so that ultimately the metal in the heated spot is given a permanent compression set. This makes the fibers on this side shorter.

Zone 4: In this zone inversion of rotor deflection gradient is implied to lose the heat during cooling which produce tension. The fibers under tension counterbalance tension stresses on the opposite side of the rotor.

Zone 5: This area represents over-straightening zone. It is obvious that the more over-straightening of the rotor will cause the more successful straightening process.

VII. CONCLUSION

According to above discussions, local phase transformation, i.e. tempered bainite to austenite and finally martensite, is the main reason of local hardness increase in turbine rotors.

Experimental results showed that rotor bend is to be modified about 50%, by performing an exact annealing process.

The results of thermal straightening investigations showed that the behavior of bent rotor came back to initial deflection if local metal temperature were selected lower than 600°C.

Numerical results show that by reduction of heat flux value heating time would increase to achieve a required temperature. And also by reduction of heating area, shorter heating time is needed to achieve the required temperature using a constant rate of heat transfer.

Because hot spotting partially utilizes the compressive stresses set up by the weight of the rotor, its application is limited and care must be taken to properly support the shaft. Thus the maximum point of bending is the best position for heating.

Previous investigations indicated that, moisture insulation causes the maximum restraint effects around the hot spot area. Also insulation would prevent annealing from wasting heat.

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