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Application of Hot Spotting Method for the Straightening of a Large Turbine Rotor

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ABSTRACT

Different problems may cause distortion of the rotor, and hence vibration, which is the most severe damage of the turbine rotors. Different techniques have been developed for the straightening of bent rotors. The method for straightening can be selected according to initial information from preliminary inspections and tests such as nondestructive tests, chemical analysis, run out tests and also a knowledge of the shaft material. HIP turbine rotors operate in a specific temperature range. Among many problems that occur during the service life of rotor few important issues are temper embrittlement, creep, thermal fatigue, corrosion, and local distortions. According to test results, hot spot straightening method was studied. Experimental studies were carried out at 16 stages. The experimental results showed that selecting a large hot spot area will not lead to the required straightness, but by reducing the heating area, the heating time decreased, and the straightening process achieved a satisfactory amount of reverse deflection. Heating the overlapped areas produces undesirable effects, such as local residual stress and/or hardness and cracks; moreover, it is not effective in straightening. Use of the finite element method before practical hot spotting is recommended to achieve satisfactory results.

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1. INTRODUCTION

In general, the causes of rotor bends can be classified invariably into two categories: rapid and slow forming permanent rotor bends. The major factors that fall into the former category include mainly rubbing and thermal shocks. Permanent deflection of rotors due to rubbing is essentially caused by the rotor transversal vibration, which causes an elastic rotor deflection at the antinodes points along the rotor. Consequently, due to the lack of clearance between the rotary and stationary turbine parts, an unwanted axisymmetric friction occurs on the surface of the maximum deflected point along the rotor, and thus the rubbed point is heated instantly, and the yield strength of the rotor material decreases. Then, the material enters the plastic zone for creating a permanent rotor bend, which is one of the most commonly encountered causes [1].

Over many years, different techniques, such as cold mechanical and thermo mechanical straightening, heating and cooling, machining, peening, welding and hot spotting, have been developed to straighten deformed members by the precise application of heat, hammer blows, or transverse force, alone or in combination [2]. The purpose of straightening is to re-establish the balance of the stresses in the rotor/shaft by exposing it intentionally to tensile and compressive stresses [3].

The heat straightening method is based on the restrained thermal expansion of metal, causing an upsetting action. Holt et al. wrote one of the first technical papers on heat straightening. They addressed the power of thermal contraction and its effectiveness in the dimensional modification of structural steel members and procedures for heat straightening damaged steel members with various configurations. The paper addresses the effects of external restraints and the application of different heating patterns, such as line heat, spot heat, strip heat and vee heat. Subsequent studies have provided substantial scientific data using experimental and analytical studies to support recommendations for damage assessment, the

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optimization of heat straightening techniques, and the development of heat straightening repair procedures [4].

In general, it is needed to investigate the following objectives prior to heat straightening research: heating temperature, heating time, dimensional measurements, geometric of heating pattern, material property, external and internal restraining forced, and quenching media [5].

2. HOT SPOTTING METHOD

Hot spotting method is generally the most satisfactory with large-diameter shafts. It is also the preferred method of straightening shafts where the bend occurs in a constant diameter portion of the shaft (i.e., between discs) [6].

Hot spotting is one of the most complex but successful of the available straightening methods. The practitioners of this method have traditionally been very secretive about their art, so it is worthwhile to explain the underlying mechanisms and the possible variations in some details [7]. It involves rapid heating of the extrados of the bend with a suitable torch, and consequently local plastic deformations (compressive stresses) are produced. Then, the material is cooled down, producing tensile stresses that contribute to the internal compensation of stresses [8] (Figure 1). To reach an effective straightening, the related practitioner must pay close attention to parameters such as local metal temperature, hot spotting time, the position of maximum distortion, cooling media and the correct control of restraint. To achieve a desired straightening effect, the local material temperature must exceed $600°C$ and will usually require a temperature of $700±10°C$ (cherry red). Ideally, metal temperatures are checked by using a thermo graphic camera [9].

It is necessary for the hot spotting temperature not to exceed 750°C; because, in that condition, local transformation to austenite will occur. In addition, upon heat removal, the cooling action of the surrounding cool material locally transforms this zone to marten site [9].

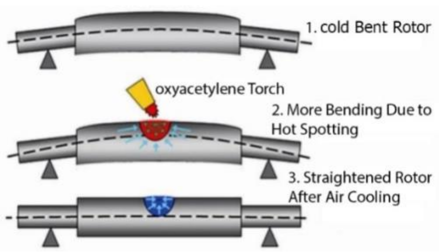

Figure 1. A simple procedure for the hot spotting method

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 the 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 the metal in the heated spot ultimately is given a permanent compression set, which makes the fibers on this side shorter, and, by tension, they counterbalance tension stresses on the opposite side of the shaft, thereby straightening it [6].

Previous investigators have indicated that the residual stress and the hardness distribution occur by reheating the same area and/or overlapping hotspots, which causes cracks. Thus, it is very important to ensure that hotspots remain discrete and are not overlapped. It is, of course, not possible to rehotspot in the same place if a bend develops on the some future occasion [1, 10].

After finishing the procedure and machining the defective (plastically upsetting) area, a non-destructive examination is applied to ensure that there is no defect and that the measured eccentricity is not outside of the standard limit.

3. CASE STUDY

In April 2006, a 325 MW steam turbine rotor failed during its operation after approximately 30000 hours in service. In fact, this failure was due to local bends at balance piston by reason of an unexpected contact between the rotary and stationary parts. After receiving the initial information, the hot spot straightening method was adopted to the available facilities. Experiments have shown that the rotors are very sensitive to the heating and cooling period and the distribution of the temperature through the hot spot area.

3. 1. EXPERIMNTS

The visual inspection of the rotor revealed available defects especially at the location of the balance piston and seals of HP blades, which illustrated that the rotor suffered from rubbing.

The rotor was subjected to chemical analysis and crack detection by a liquid penetrant examination. The results of chemical analysis in Table 1 were compared with the standard steel specified by ASTM A470, and it was demonstrated that the rotor material is adaptable to the aforementioned standard steel.

To investigate the micro structural variations on the bent area of the rotor, the surface replication technique and hardness measurements were used. The microstructure of the rotor was found to be fully in the bainitic phase (Figure 2).

To determine the extent of bending, an initial run-out test was performed on the rotor.

TABLE 1. Chemical composition of the rotor steel.

Element	C	Si	Mn	P	S	Cr	Ni	Mo	V
Weight Percent	0.29	0.27	0.80	0.011	0.013	1.32	0.45	1.01	0.23

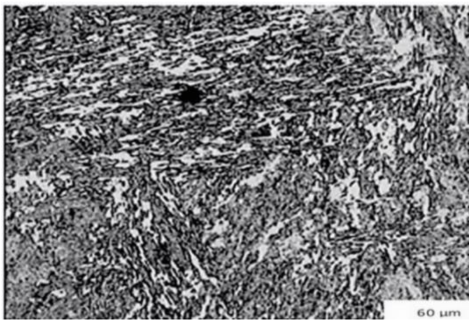

Figure 2. The bainitic structure of the bent rotor

The results of initial run-out tests at three various angles (90°, 180°, 270°) in Figure 3 indicated that the rotor has a maximum run-out about 1.7 mm, at exactly the opposite side of the maximum rubbing area in the position of balance piston.

3. 2. ANNEALING The next step was the annealing process with the purpose of reliving the residual thermo mechanical stresses induced by rubbing. Nine thermocouples were spot welded as close as practicable to the heated zone to control the rotor temperature during the annealing process.

The heating process was performed locally on a complete circumferential band at the bent area of rotor. The tempering procedure was performed according to the curve in Figure 4. The results of calculations and experimental investigations had shown that a rate of 30°C/h for the heating and cooling, and the temperature of 680 °C with the holding time of 12 hours are the optimum states in the tempering process [11].

After annealing, the rotor was completely inspected both visually and by dye check. The results showed no surface cracks or flaws. A hardness test signified that the measured hardness values were within the standard range of the rotor steel. Moreover, the results of the run out test showed that the maximum value of bending was reduced from 1.7mm to 0.85mm. In other words, according to this process, rotor bending was modified by approximately 50% [11].

3. 3. Hot Spotting Process In this stage, the rotor was set up in a lathe supported by steadies at the free end so that was free to lengthen without restriction to accommodate thermal expansion during hot spotting process. The shaft was then rotated until the determined maximum eccentricity position, placed at the top of the shaft. The maximum bent position was then locally heated by the application of two oxyacetylene torches with the large nozzles, adjusted to give a soft flame within a short period of time (Figure 5(a)). Three dial indicators were positioned exactly 180° from the hot spot area (i.e., underneath the rotor). Torches were applied to the top of the shaft, i.e., the point of maximum bending, causing the shaft to rise locally, as shown in Figure 5(b) for the sixth attempt of hot spotting.

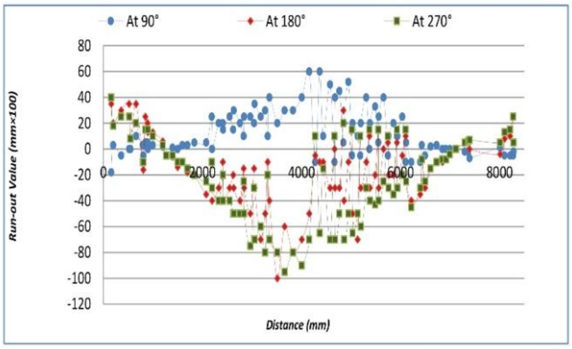

Figure 3. Results of the initial run out test at three angles

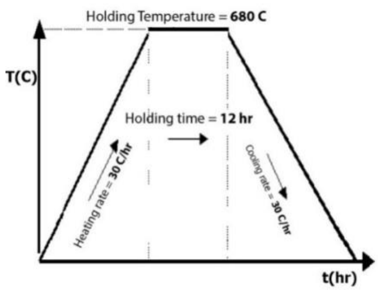

Figure 4. The tempering heat treatment process curve

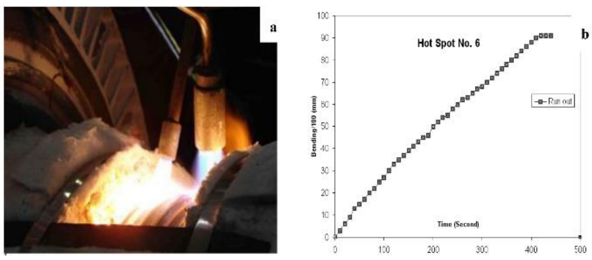

Figure 5.(a) The application of two torches to heat the area of maximum bending and (b) its result on bending during the heating time

To achieve acceptable rotor straightness, this thermal process was performed sixteen times, and, after each three or four times, visual inspection, dye check & hardness tests and annealing processes were performed in accordance with the descriptions given in previous sections to check rotor defects.

Torch movement was limited to the particular area of hot spotting and heating was stopped before the maximum temperature (700-710°*C* in this process) was exceeded. Upon heat removal, the cooling of the material was performed using compressed air flow. This process led to an elastic contraction which could significantly modify the bent rotor.

Table 2 shows the results of hot spotting for fourteen attempts of straightening. At stage 1, the hot spot area was exactly at the maximum bending point. At the next stage, although the heating time noticeably lessened, hot spotting was not effective enough because changing the hot spot position 20mm axially and 100mm circumferentially caused overlapping with the previous hot spot area. The additional stages were performed similarly.

The run out measurement shows that stages 6 and 10 have the most reverse deflection values among stages 3 to 6 and 7 to 10, respectively, which have the same size of hot spot area. Attention to details demonstrated that the reduction of heating time caused to achieve the satisfactory results in stages 6 and 10.

Although heating time in stage 11 was 460 s, the amount of reverse deflection at the maximum bending point was 5×10^{-2} mm because the heating area at this stage completely overlapped with the last heated area. Hot spot area and heating time of stage 12 seems to be better than others but the results did not lead to a satisfactory straightness because the heated area was axially 180 mm away from the maximum bending point.

The ineffectiveness of stages 9, 13 and 14 shows that plasticity was not occurred up to the temperature of 610°C. Stages 15 and 16 were not mentioned because they were completely abortive.

In the final step of straightening process, accurate completion of machining of the upset area was performed to remove it, and then the run out test was conducted at three angles. The results in Figure 6(a) show a noticeable reduction in eccentricity. A comparison between run out values before and after straightening at an angle of 180° is shown in Figure 6(b).

The analysis of the all sixteen stages illustrated that the heating process would be effective when it was done at the position of maximum bending, exactly at the first attempt after annealing process. Also reheating on exactly the same position is ineffective.

Considering hot spotting condition include: phase transformation at the heated area, resulted thermal stresses during the process and frequently heating and cooling (16 times), etc. even a small mistake can cause a severe damage to the rotor. Therefore, it is recommended to apply the numerical analysis before the hot spotting for various conditions and optimize all the stages of straightening execution to prevent from probable damages.

TABLE 2. Experimental results of hot spot straightening for eleven stages.

Stage	Hot Spot Area (mm^2)	Heating time (s)	Temperature (°C)	Increase in Bending After Heating ($mm\times10^2$)	Cooling Time (s)	Reverse Deflection ($mm\times10^2$)at Maximum Bending Point
1	90×290	900	700	119	900	8
2	90×290	660	690	102	900	5
3	100×360	680	700	129	900	10
4	100×360	-----	710	148	600	7
5	100×360	780	710	143	900	10
6	100×360	430	710	91	1200	15
7	80×360	620	710	143	1200	11
8	80×360	870	710	166	1200	7
9	80×360	----	610	----	----	0
10	80×360	480	710	110	1200	15
11	110×380	460	700	121	1200	5
12	80×340	440	700	89	1200	13
13	----	420	560	100	----	0
14	----	----	480	----	----	0

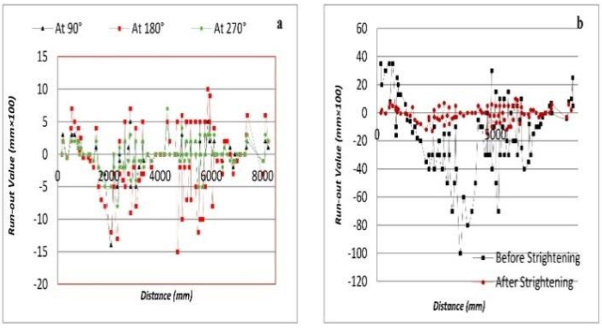

Figure 6. The results of run out test (a) after straightening and (b) their comparison, before and after straightening at an angle of 180°

4. FINITE ELEMENT ANALYSIS

4. 1. Modeling and Simulation Since the hot spot straightening process is a completely experimental method, it is very sensitive, and its control is complicated. Hence, a 3D finite element simulation of a HIP steam turbine rotor was performed using ABAQUS software. In this simulation, the whole rotor was divided into 20 partitions and each partition meshed by using a suitable element type (Figure 7), structural mesh also was applied in critical areas around the hot spot zone. To achieve a good coverage for satisfactory resolution, meshing was refined by the number of 72011 elements. Mechanical and physical properties of the rotor material were exerted to the model according to Table 3. In addition, the convection coefficient was defined for the hot spot area during cooling time.

The hot spot area was modeled with different geometric sizes (Table 4) and corresponding heat fluxes during heating time to simulate various conditions.

4. 2. Heating The initial temperature condition was assumed as a uniform temperature of 21°C. The type of analysis was coupled temperature-displacement and transient response. The results of the first simulation for a model with a heat flux value of $257\times10^3\ w/m^2$ and a 182×404 mm^2 rectangular hot spot area in Figure 8 indicate that no plastic strain will occur when the temperature of the hot spot area increases to 710°C over 1580 seconds. Hence, as it was shown at the experimental study (stage 11), an excessive hot spot area would be ineffective and it causes to damage the rotor.

In the second simulation, different heat flux values were exerted on a 130×323 mm^2 rectangular hot spot area at the maximum point of bending with 323 mm along the perimeter of the rotor and 130 mm along the axis of the rotor. Figure 9(a) shows the graphs of temperature versus time for the hot spot straightening process on a specific area with the aforementioned dimensions and various heat flux values. Heat flux values of $450\times10^3\ w/m^2$, $475\times10^3\ w/m^2$ and $500\times10^3\ w/m^2$ were applied to the cases (A), (B) and (C), respectively, which provided an effective temperature of 708°C for the hot spot area during different heating times.

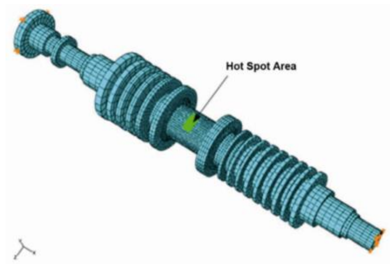

Figure 7. Finite element model of the rotor

TABLE 3. Mechanical and physical properties of the rotor material

Temperature (°C)	21	100	200	316	427	538	649	700
Yield Strength (MPa)	547	531.6	500	467	432	356	204	100
Thermal Conductivity (W/m.K)	---	38.9	38.1	36.9	31.9	29.2	24.2	---
Elastic Modulus (Pa×10^{-9})	215	207.3	200	191	183	170	156	150.3
Expansion Coefficient (m/s^2)×10^{-6}	10.9	9.9	---	8.1	---	6.2	---	3.9
Specific Heat (J/kg.K)	431.5	479	---	570.4	---	694.2	---	931.1

TABLE 4. Dimension of the hot spot area

	First Simulation	**Second Simulation (Cases A, B and C)**	**Third Simulation (Cases D, E and F)**	**Forth Simulation (Case G)**
Axial Direction (mm)	182	130	104	78
Perimeter Direction (mm)	404	323	243	162

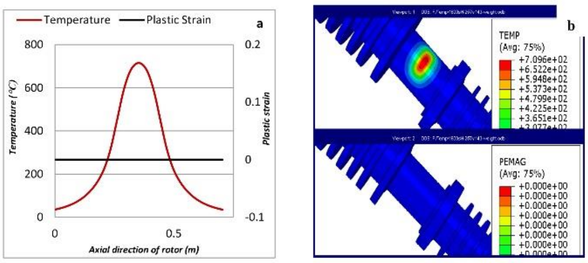

Figure 8.(a) Thermal distribution and plastic strain along the axial direction of the rotor and (b) their contours at a temperature of 710°C

Stress distributions for three aforementioned cases at 708 °C show that, with the approach to the boundary of heated area, the stress level increases (Figure 9(b)). The highest stress level is around the heated area, and its value in case (C) is higher than others, and thus it is ideal for achieving improved straightness. This figure also indicates that, in the middle of the hot spot area where the temperature is at a maximum, the stress value falls with a sharp slope.

Graphs of plastic strain magnitude along the axial direction of the rotor (Figure 10) show that case (C) has the largest extent of plastic strain. Although the simulation of other cases show that plastic strain occurred in the middle of hot spot area, their magnitudes were not sufficient to achieve the required straightness as conveniently as in case (C).

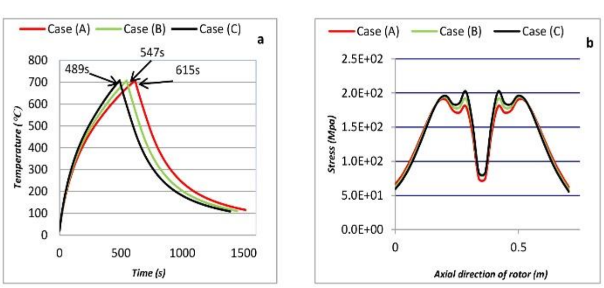

Figure 9. (a) Temperature distribution of the hot spot area with various heat fluxes and (b) stress distribution along the axial direction of the rotor

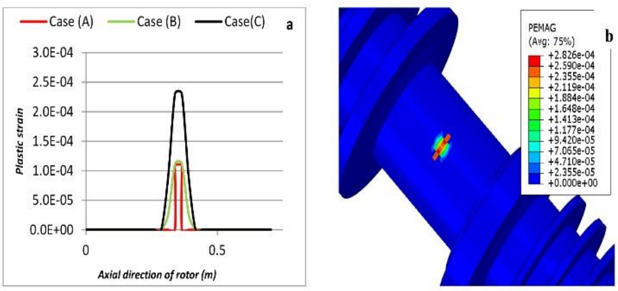

Figure 10. (a) Plastic strain magnitude along the axial direction of the rotor and (b) its contour

The hot spot area was modeled with different geometric sizes (Table 4) and corresponding heat fluxes during heating time to simulate various conditions.

In the next arranged simulation, three calculated heat flux values were exerted on a 104×243 mm^2 rectangle at the maximum bending point of the rotor. Figure 11(a) shows that the third simulation with a smaller hot spot area and the same rate of heat transfer provides an effective temperature over a shorter period of time. Cases (D), (E) and (F) obtained a temperature of 710 °*C* over 275 s, 250 s and 227 s, respectively.

According to Figures 11(b) and 12 and referring to the above discussions, case (F) leads to the best straightening in the third simulation.

The simulation of case (G) was arranged for a model with a 78×162 mm^2 rectangular hot spot area and the same rate of heat transfer as in case (C). Comparison of the plastic strain along the axial direction of the rotor between cases (C) and (G) in Figure 13(a) demonstrates that the reduction of the hot spot area causes a larger magnitude of plastic strain, which is ideal for improving the hot spotting results. Moreover, making a comparison between diagrams of stress along axial direction of the rotor (Figure 13(b)) for cases (C), (F) and (G) proves that case (G) gives the optimum time, heat flux and area of hot spotting and as well as a sufficient hot cherry red area and more restraint effects.

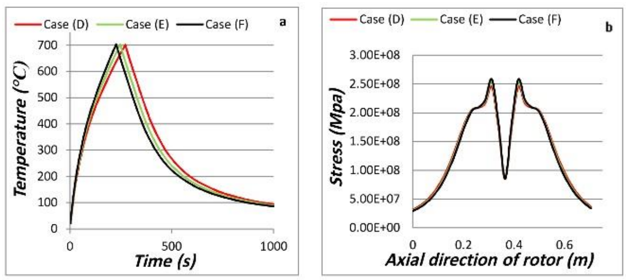

Figure 11. (a) Temperature distribution of the hot spot area with various heat fluxes and (b) stress distribution along the axial direction of the rotor

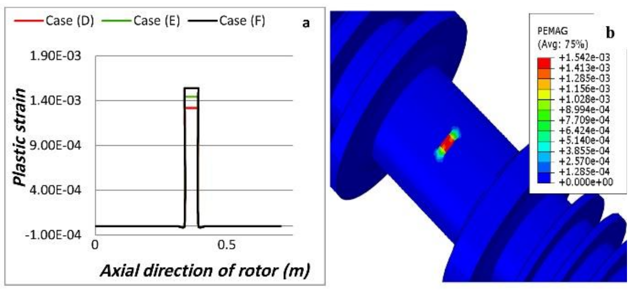

Figure 12. (a) Plastic strain magnitude along the axial direction of the rotor and (b) its contour

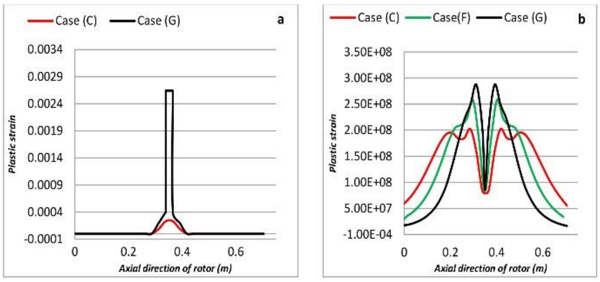

Figure 13. (a) Plastic strain distribution and (b) stress distribution along the axial direction of the rotor after the heating step

However, there are, some practical limitations such as the adverse effects of thermal shocks, and the shortage of equipment that may prevent practitioners from heating an area as small as the hot spot area in case (G). Hence, considering the available equipment and applicable conditions, case (F) was selected as the practical optimum case.

In case (H), the heating process of case (F) was conducted for approximately 25 *s* longer until a temperature of 752 °C was obtained to investigate the effects of extra heating. Although Figure 14 shows an insignificant increase in the magnitude of plastic strain along the axial direction of the rotor, Figure 15 shows that the area of plastic strain would significantly extend along the perimeter of the rotor. The yielding of the material through this large plastic area would contain extra energy to increase the distortion of the rotor with no control. On the other hand, according to previous investigations, exceeding the permutation temperature will cause undesirable effects on the material structure.

Figure 16 draws a comparison between the resultant thermal stresses of case (F) and the yield strengths at different temperatures. Although the yield strength of the material decreased during the heating process, but the available thermal stresses cannot reach the yield point before a temperature of approximately 600 °C because the resultant thermal stresses begin to fall after achieving to their peak value at a temperature of 425°C. Thus, at the temperature of 600 °C, thermal stresses begin to overcome the material strength, and the plastic area begins to appear.

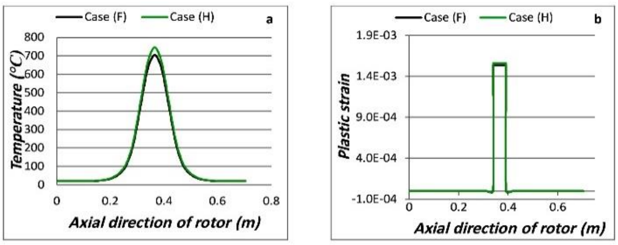

Figure 14. Comparison of (a) temperature and (b) plastic strain along the axial direction of the rotor between cases (F) and (H)

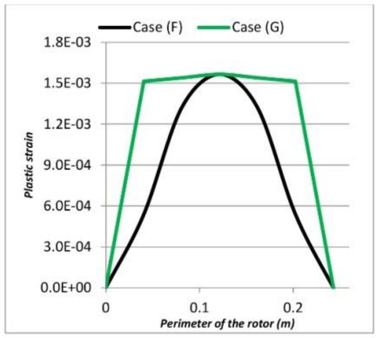

Figure 15. The plastic strain versus the perimeter of the rotor

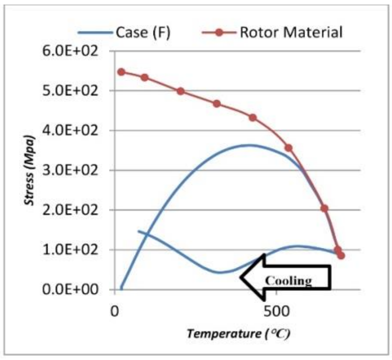

Figure 16. Stress variations during hot spotting

4. 3. Cooling In all of the previous simulations, cooling process was done during 15 minutes by using compressed air. Maximum temperature of the rotor surface was about 100°C after the cooling. In practical state, after aforementioned process the rotor rotates slowly about two hours on a lathe until the surface temperature reaches to the room temperature.

Figure 17 shows stress distribution curves for two various convection coefficients of 125 W/m^{2}K and 250 W/m^{2}K during the straightening process for the case (F). It is indicated that the slope of stress increased at the beginning of the cooling (227 s) is not sufficient for both of the curves. So, the convection coefficient variations have no effect on the result. It means using dry compressed air to cool the rotor by the forced convection coefficient is not more effective than cooling by natural convection, because by using compressed air the stress level do not increase significantly.

4. 4. Optimization Software and Discussion In order to achieve the optimum condition of the hot spot straightening at various states, a program was written using MATLAB software. In this program, the available simulation outputs were utilized as the optimum conditions. By selection an area to heat, the corresponding optimum heat flux is calculated and then heating time and bending increase and decrease are achieved in accordance with them. The interpolation method used to write the program.

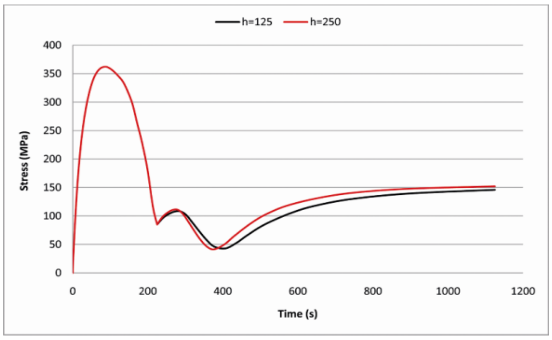

Figure 17. Comparison of stress distribution curves with two different convection coefficient during cooling

Table 5 draws a comparison between the experimental data and received numerical results by the programming with the similar heating area.

According to the numerical results in Table 5, the ratio of the bending decrease after cooling to the bending increase after heating (straightening rate), is enhanced by reduction of hot spot area. In other words, the amount of reverse deflection is increased, but the inaccuracy of this fact in the experimental results is caused by several reasons described below in detail.

Although in stage E_6 which had one of the best experimental results, hot spotting was done at the maximum bending location immediately after the annealing process, the numerical result is far better than it. Since the dominating condition during the simulation is more perfect than the experiments, it is understood that experimental heating time should be longer than numerical to cause a sufficient plastic strain and subsequently the same reverse deflection.

Reduction of the hot spot area and also an increase in the actual heating time in stage E_{10} than E_6, has dwindled the difference between the experimental and numerical results. Although it was expected that the stage E_{10} achieves better results than the stage E_6, destructive effects of previous stages (hardening of the surface) cause to achieve a same amount of reverse deflection.

Although in stage E_{12} the 233 s time difference between the actual and optimum heating time and also 180 mm distance difference between the position of heating area and maximum bending area are undesirable items, this stage has one of the best results. In accordance with the simulations, because of the small heating area, stage E_{12} caused an acceptable reverse deflection.

Applying an insufficient heat flux value and corresponding heating time in stage E_1 caused to decrease the restrain effects of the rotor material around the hot spot area and subsequently an undesirable experimental result despite the fact that an appropriate area was heated.

In the stage E_{11} the actual heating time is approximately optimum, but as it was stated above, the actual heating time should be more than numerical to achieve the best results. Moreover, the difference between the bending increase & decrease, during the straightening process and subsequently its unsatisfactory reverse deflection caused by heating the overlapped areas. In addition, selecting a large heating area was prevented to provide an enough plastic strain zone after heating.

5. CONCLUSION

By making a comparison of the experimental reverse deflection between the stages E_6, E_{10} and E_{12}, it is demonstrated that only expansion of the heat area along the perimeter direction is improved the final result not along the axial direction.

TABLE 5. Comparison of the Experimental(E) Results with the Optimum(O) State.

Stage	Hot Spot Area (mm)	Heating Time (s)		Increase in Bending After Heating(mm×10^2)		Decrease in Bending After 20min Cooling(mm×10^2)		Straightening Rate		Experimental Reverse deflection (mm×10^2)
		Ex	Op	Ex	Op	Ex	Op	Ex	Op	
E_1	90×290	900	259	119	97	-----	77	----	0.79	8
E_6	100×360	430	427	91	133	39	62	0.43	0.47	15
N_1	90×315	----	302	----	105	-----	77	----	0.73	----
E_{10}	80×360	480	311	110	107	60	77	0.55	0.72	15
N_2	115×290	----	384	----	123	----	75	----	0.61	----
E_{11}	110×380	460	461	121	147	64	79	0.53	0.54	5
N_3	130×380	----	505	----	184	----	83	----	0.45	----
E_{12}	80×340	440	207	89	89	45	68	0.51	0.76	13

Upon achieving an optimum area expansion will no longer effective.

The experimental results showed that selecting a large hot spot area will not lead to the required straightness, but by reducing the heating area, the heating time decreased, and the straightening process achieved a satisfactory amount of reverse deflection.

Heating the overlapped areas produces undesirable effects, such as local residual stress and/or hardness and cracks; moreover, it is not effective in straightening. Therefore, straightening execution over a shorter time using a higher heat flux value through a smaller area has more desirable results.

The numerical analysis results do not support the selection of an excessively sized hot spot area because this will not produce plastic strain at or below 710 °C. It was also shown that a reduction of the heating area improves the results of hot spotting. The numerical results also indicated that selecting a 78×162 mm^2 rectangular hot spot area led to more satisfactory results, because a short heating time causes a high local temperature and the adverse effects of thermal shocks. However, a drastic change in stress which raises the possibility of the rotor damage prevents practitioners from heating an area as small as the aforementioned area. Thus, a 104×243 mm^2 rectangular hot spot area, a heat flux value $833.35\times10^3\ w/m^2$ and a heating time equal to 227 s were selected as the practical optimum conditions required for straightening the investigated rotor. The optimized time provides a suitable thermal gradient and, consequently sufficient thermal stress.

The temperature of 700-710 °C is conservative to prevent the occurrence of marten site transformation because exceeding the aforementioned temperature would cause a local phase transformation (i.e., tempered bainite to austenite and finally marten site) and local hardness.

The results of thermal straightening investigations showed that the behavior of the bent rotor would return to its initial deflection if the local metal temperature were lower than 600 °C. In other words, the nature of resulted thermal stresses was essentially elastic, i.e., smaller than the yield stress.

However, by increasing the heating temperature (in the same state) up to 700-710 °C, threshold plastic deformation occurred due to the thermal stress increment and consequently compressive yielding.

In accordance with the achieved results, using dry compressed air to cool the rotor by the forced convection coefficient is not more effective than cooling by natural convection.

According to these findings, use of the finite element method before practical hot spotting is recommended to achieve satisfactory results, as the likelihood of damages and faults will be reduced.

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Application of the Hot Spotting Method for the Straightening of a Large Turbine Rotor

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چکیده

مسائل متعددی ممکن است موجب اعوجاج روتور و در نتیجه ارتعاش آن شود که بروز خسارات شدید در روتور توربین‌ها را سبب می‌گردد. تاکنون روش‌های مختلفی برای رفع خمش روتور، توسعه یافته است. روش خمش زدایی می‌تواند بر اساس اطلاعات اولیه‌ای که از بازرسی‌های مقدماتی و آزمایشات مختلف از قبیل تست‌های غیر مخرب، آنالیز شیمیای، آزمایش سنجش ماکزیمم خمش و همچنین اطلاعاتی که از مواد شفت بدست می‌آید، انتخاب گردد. روتور توربین‌های فشار بالا در محدوده دمایی خاصی کار می‌کند. در میان مشکلات متعددی که در حین عملکرد روتور اتفاق می‌افتد، موضوعات مهم‌تر عبارتند از تردشدگی بازپخت، خزش، خستگی حرارتی، خوردگی و اعوجاج موضعی. در پی نتایج آزمایشات انجام شده، رفع خمش به روش گرمایش موضعی مورد مطالعه قرار گرفت. نتایج تجربی حاصله نشان داد که گرم کردن یک ناحیه وسیع نتیجه مطلوبی را درپی نخواهد داشت، اما با کوچک‌تر کردن مساحت ناحبه گرمایش، زمان گرمایش کاهش یافته و در نتیجه پروسه خمش زدایی، میزان برگشت خمش رضایت بخش‌تری را نتیجه خواهد داد. همچنین دوباره گرم کردن موضع گرم شده نتایج نامطلوبی نظیر ایجاد تنش‌های پسماند و/یا افزایش سختی و ترک را درپی خواهد داشت و علاوه بر این اثر مثبتی در کاهش خمش نخواهد داشت. جهت دستیابی به نتایج رضایتبخش، استفاده از روش المان محدود قبل از عملیاتی کردن این روش توصیه می‌گردد.

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