TECHNICAL NOTE

THE CAUSES OF LOCAL HARDNESS INCREASING IN POWERPLANT ROTORS AND ITS MODIFICATION BY TEMPERING

E. Poursaeidi*

Department of Mechanical Engineering, Zanjan University
P. O. Box 313, Zanjan, Iran
Iran Power Plant Repair Company, Research and Laboratories
P. O. Box 31585/1137, Karaj, Iran
epsaeidi@yahoo.com - epsaeidi@znu.ac.ir

A. R. Razavi

Iran Power Plant Repair Company, Research and Laboratories
P. O. Box 31585/1137, Karaj, Iran
arazavi110@yahoo.com

*Corresponding Author

(Received: October 10, 2006 – Accepted in Revised Form: May 9, 2008)

Abstract Local hardness increasing on the surface of the power plant rotor may result in severe damages. One major solution for rapid repairing of the rotors is the adaptive tempering heat treatment. For this purpose, after identification of the damaged rotor, initial investigations and tests (such as visual inspection, chemical analysis, nondestructive hardness measurements and replica or on-site metallographic tests) were performed on the rotor journal. The results showed that, the occurrence of local phase transformation (i.e. tempered bainite to austenite and finally martensite) is the main factor. Finally, based on the aforementioned results, tempering heat treatment method was selected as a modifying solution for the following purposes: 1. Decreasing hardness in embrittled places (i.e. 400-690 HV) and, 2. invariable or admissible decrease of hardness in undamaged areas (250-300 HV). Experiments showed that by choosing the 680°C/4hr as an optimum condition for tempering heat treatment, the two mentioned objectives can be met.

Keywords Hardness, Power Plant Rotors, Tempering Heat Treatment

چکیده منشاء افزایش سختی موضعی در سطح روتورهای نیروگاهی که گاهی اوقات عملکرد روتور را دچار اختلال می کند، فراوان است. در این مقاله اصلاح محل های تحت سایش ژورنال روتورهای نیروگاهی که به علت ایجاد اختلال ناگهانی در سیستم روغن رسانی مابین شفت روتور–یاتاقان دچار افزایش سختی موضعی شده‌اند، به روش عملیات حرارتی تمپرینگ بررسی شد. به همین منظور، پس از انجام تست سختی سنجی (غیرمخرب)، مشخص شد که علت اصلی افزایش بیش از حد سختی با دامنه پراکندگی فراوان (HV ۶۹۰–۴۰۰) عمدتاً استحاله فازی مارتنزیتی است. عوارض ناشی از تنش مکانیکی در حوالی محل های مزبور بر این اساس با سیکل عملیات حرارتی تمپرینگ بر طرف شد. مبنای طراحی سیکل های عملیات حرارتی تمپرینگ در جهت تامین دو هدف استوار گردید: کاهش سختی محل های آسیب دیده ژورنال روتور در حد قابل قبول (HV ۶۹۰–۴۰۰) ضمن عدم کاهش سختی یا کاهش معقول سختی محل های سالم (HV ۳۰۰–۲۵۰). لذا سیکل عملیات حرارتی با انتخاب دمای ۶۸۰°C و زمان ٤ hr به عنوان حداقل دما و زمان بهینه برای تأمین دو هدف مزبور به مورد اجرا گذاشته شد. حذف نواحی ترد (محل های دارای حداکثر سختی) و کاهش دامنه پراکندگی سختی در سطح ژورنال روتور، از جمله نتایج این پروژه است.

1. INTRODUCTION

Turbine rotors are among the most critical and highly stressed components in power generating plants [1].

Low alloy steel (ASTM 471/NiCrMoV, ASTM

A470/CrMoV) are used to manufacture rotors for high, intermediate and low temperatures [2]. The operating condition under which the failures occurred is deduced form the morphology of damaged area and the changes in microstructure [3]. Depending upon applied temperature and pressure, some damages occur gradually during long-term service. These damages include embrittlement, creep, thermo-mechanical fatigue, corrosion, and so on, which are related to inherent material properties. Additionally, some factors such as thermal shocks due to premature shut downs or trips, locally rubbing and erosion due to inadequate installation and conditions can be categorized as susceptible factors to occurrence of some damages (asperities, cracking, etc) [4].

In the current study, the major factor, which may cause catastrophic events (i.e. rubbing due to the loss of clearance between rotating and stationary turbine parts), was investigated. The mechanism of aforementioned phenomenon, which is one of the most commonly encountered with all kinds of rotor journal, is described in the following sections.

The journal bearings are those parts of turbine which support the rotor. Their function is to ensure proper alignment of the parts in the cylinder during operation. When the rotor is in rotation, the friction arises between the bearings. That portion of the shaft which is located in the bearings is called shaft journal.

The bearings should be constructed to minimize the power losses due to friction. For this reason, a babbit (tin-base alloy) lining covers the surface of bearing shell with a given thickness. When two surfaces are rubbing against each other, the forces of friction will reach its maximum and that's when the friction is dry, i.e. when there is no lubricant between the rubbing surfaces. These forces will be at minimum when these surfaces are separated by a layer of lubricant. Therefore, the lubricant is always delivered to the bearing through channels originated from main/auxiliary oil supply pump. Obstruction/limiting the channels due to any reason stop the lubrication system [5]. This event leads to hardening of steel due to frictional heating and subsequent cooling. Therefore, the tempering heat treatment method has been selected as a modifying solution [6] for the following purposes:

- To decrease the hardness in embrittled places up to reference values
- Invariable or admissible decrease of hardness in undamaged areas

2. SCIENTIFIC BACKGROUND

When hardened steel is exposed to any thermal/mechanical process similar to aforementioned phenomena (in the introduction), it changes into tetragonal martensite with a certain amount of retained austenite [7]. The main difficulty with using steels in hardened condition (in which martensitic structure is present) is reduction in its toughness. Thus, in most applications of power plant rotors where relatively intermediate hardness (220-280 HV) is required, the rotor steel must be modified by heat treatment, in order to convert the martensite to a structure of fine carbide particles in ferrite. This structure has a lower hardness than that of martensite, but by proper choice of temperature and time, the developed structure will be sufficiently fine to give the desired hardness. In this condition, the martensite has been replaced by a tougher structural component. This heat treatment is called tempering, and the main purpose is to develop a usable combination of hardness and toughness.

Tempering of microstructures other than martensite and retained austenite also represents special applications of tempering. Reactions of

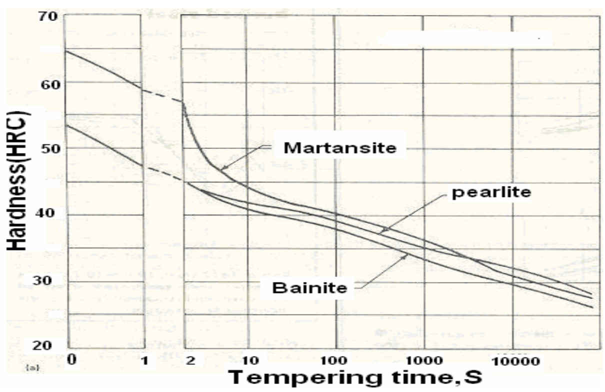

Figure1. The effect of microstructure on hardness during tempering [8].

structures containing substantial amounts of lower bainite are relatively similar to martensite in terms of the phenomena associated with carbide growth and coalescence. Upper bainite and fine pearlite formed by controlled or relatively slow cooling, simply respond by carbide growth and eventual ferrite re-crystallization (Figure 1) [7,8].

In addition, tempering is used to relieve the stresses induced by any thermal/mechanical processing (e.g. welding, forming, machining, rubbing) and ensure dimensional stability [9].

3. PRINCIPAL VARIABLES

Variables associated with tempering that affect the microstructural and mechanical properties of tempered steel include:

- Tempering temperature
- Holding time
- Cooling rate
- Composition of the steel, including carbon content (mainly) and alloying elements

3.1. Tempering Temperature It is obvious that variation of mechanical properties (especially hardness) depends on microstructural changes due to essential thermal influences according to the following sequences:

❖ At a temperature between 80 and 200˚C, a carbon- rich transition product known as carbide is precipitated from the tetragonal martensite, reducing the lattice to cubic ferrite. This reaction is called the first stage of tempering. During this period, due to the release of carbon, the martensite lattice contracts in volume.

❖ At a temperature between 200 and 300˚C, the retained austenite is decomposed in to a bainite-like product, a state of aggregation similar to tempered martensitic, and the transformation is called the second stage of tempering. At this stage, there is an increase in the volume of steel.

❖ At a temperature between 300 and 700˚C, the growth continues and spheroidization of carbides takes place.

❖ At higher temperatures, the formation of more complex carbides take place in steel in which strong carbide forming elements are present. This process is designated as the fourth stage [10].

3.2. Holding Time Tempering accomplishes its purpose through a combination of temperature and time changes. It is not sufficient to merely heat hardened steel to some definite temperature. It must be soaked for a definite length of time. Since the diffusion of carbon and alloying elements is, temperature and time dependent, therefore in the tempering cycle, the holding time is very important to make the desired changes in properties (hardness is commonly used to evaluate the response of a steel to tempering) [7].

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 [10].

4. EXPERIMENTAL METHODS (BEFORE TEMPERING)

In order to evaluate the as-received rotor, the following tests were performed (Figure 2).

- Chemical Analysis
- Hardness Test
- Replica Test

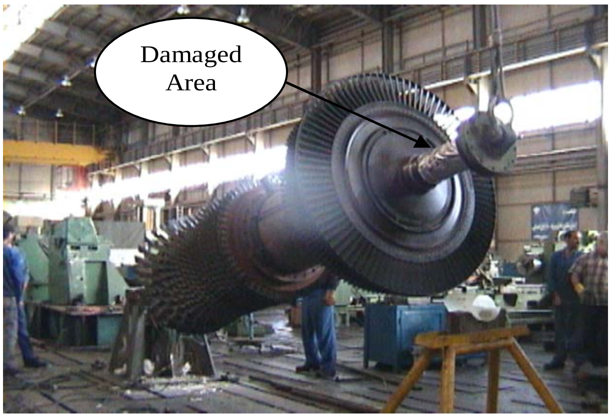

Figure 2. A general view of damaged rotor in journal position.

4.1. Chemical Analysis In order to perform nondestructive determination of the chemical composition of a rotor, a study of an optical emission analysis with ARC-MET 930S8P was carried out. The Results of the chemical analysis are shown in Table 1. These results are compared with those specified by ASTM A293 (carbon and alloy steel forgings for turbine rotors and shafts) and A470 (vacuum treated carbon and alloy steel forgings for turbine rotors and shafts) in Table 2. According to this analysis, the rotor was made of 1 % Cr-1 % Mo-0.25 % V low alloy steel, which is adaptable to ASTM A470 class 8. The mechanical specifications of this steel are presented in Table 3.

4.2. Hardness Test In order to study the variations of hardness in failed section of the rotor (i.e. journal), hardness tests were carried out on various locations in the peripheral and longitudinal directions according to Figure 3. The nondestructive hardness test was performed with Eqoutip 2 set, which had been standardized by ASTM A965-96. The results (Table 4) showed a

TABLE 1. Chemical Composition of Rotor Steel.

Element	% C	Si	Mn	P,S	Cr	Mo	Ni	V
Weight Percent	0.27	0.2	0.79	0.02	0.97	1.22	0.31	0.26

TABLE 2. Standard Composition Range of HP Rotor Steel (A470 CL. 8) [2,11].

Element	C	Si	Mn	P,S	Cr	Ni	Mo	V
Weight Percent	0.25 -0.35	0.15-0.35	0.7 -1	0.015	0.9-1.5	0.75	1-1.2	0.2-0.3

TABLE 3. Mechanical Specifications of Investigated Rotor Steel [2].

Yield Strength (≥ N/mm^2)	Tensile Strength (N/mm^2)	Hardness (HV30)
540	690-850	215-215

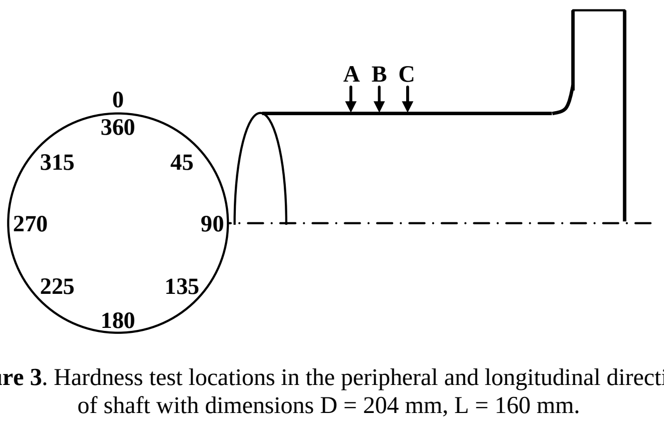

Figure 3. Hardness test locations in the peripheral and longitudinal directions of shaft with dimensions D = 204 mm, L = 160 mm.

noticeable increment of hardness values (up to 698 HV in severely rubbed zone) in comparison with reference specified limits (215-265HV) [2,11].

4.3. Replica Test (Field Metallography) In order to investigate the microstructural variations on severely embrittled zone of journal surface and comparing it with the original structure, it was decided to take nondestructive micrographs (Replica) were taken based on standard designated E 1351. Field metallography was performed by STRUERS microscope in site and PMG3 light microscope in the laboratory.

In spite of adequate grinding/polishing and etching of selected surface, no obvious variations in the phase transformations were observed. However, there were serious traces of rubbing due to contact of journal zone with stationary parts (Figure 4). The microstructure of rotor was found to be fully bainitic as shown in Figure 5.

TABLE 4. Variations of Hardness Values in the Failed Section of Rotor.

Hardness / Degree	A	B	C
0/360	266	253	238
45	265	269	298
90	260	634	409
135	286	659	508
180	235	597	590
225	269	698	508
270	280	680	418
315	256	279	251

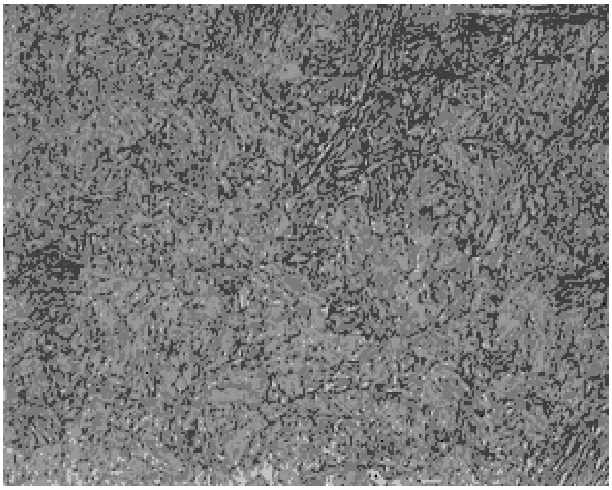

Figure 4. The micro structural variations on embrittled zone of journal surface (Etchant: 2 % Nital, 100 X).

5. RESULTS AND DISCUSSION

5.1. Discussion on Initial Tests According to the main results of initial tests, the cause of increase in hardness of the embrittled surfaces (i.e. 400-690 HV) was essentially local phase transformation (i.e. tempered bainite to austenite and finally martensite). This point may be further evidenced with respect to Continuous-Cooling-Transformation diagram (C. C. T diagram) which is illustrated in Figure 6. It has been observed that, the hardness values of more than 500 HV is related to the existence of martensitic structure As expected, the material including of martensitic structure is rarely used in an untempered condtion because a large number of internal stresses associated with the transformation cause the material to be lacking in ductility [14].

Hence, the tempering heat treatment method was selected as a modifying solution for the following purposes:

- To decrease hardness in embrittled areas (i.e. 400-690 HV) up to the reference values
- Invariable or admissible decrease of hardness in undamaged parts (250-300HV)

5.2. Discussions on Tempering Procedure

5.2.1. Tempering temperature [10] According to Jominy test results, high hardness values decrease more than low hardness. It can be seen that high hardness near the quenched area of the specimen has decreased much more by tempering than low hardness values at greater distances from the quenched end. With respect to the cross section of hardened components, this effect means that

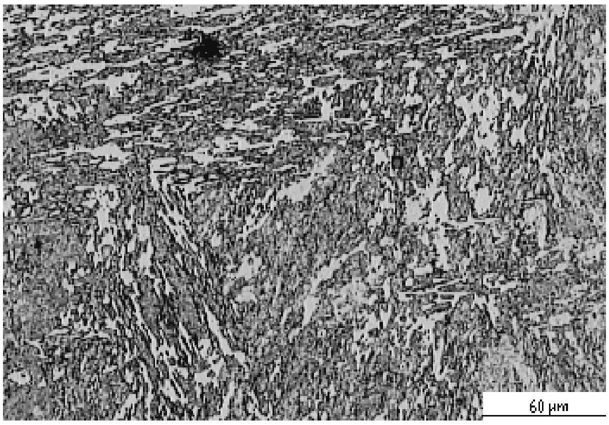

Figure 5. The safe or original structure of rotor steel (enchant 2 % Nital) [7,11].

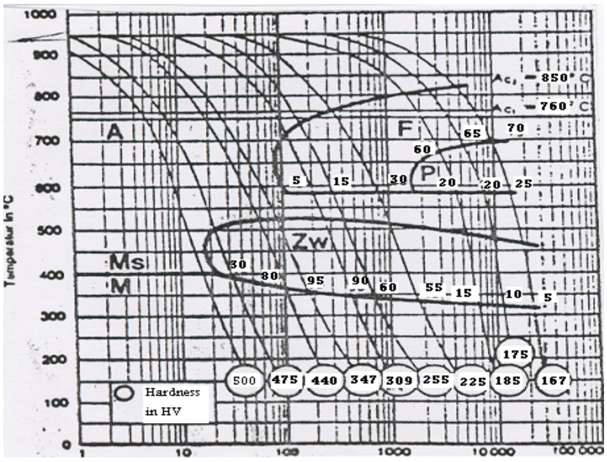

Figure 6. Continuous-cooling-transformation diagram (C.C.T) for A470/CrMoV steel [11].

tempering equalizes the hardness differences between surface and core. So, the calculations used in selection of tempering temperature and times are based on following:

Equation 1 calculated the necessary tempering temperature T_t [10]:

$$T(^\circ C)=917\left[\frac{\ln\dfrac{H_h-8}{H_t-8}}{S}\right]^{\frac{1}{6}}-273 \qquad (1)$$

where H_h is the hardness after hardening (HRC), H_t is the required hardness after tempering (HRC) and S is the degree of hardening. By substitution of measured values in formula:

H_h = 60 HRC/680 HV, H_t = 27 HRC

The degree of hardening S normally varies between 0.7 and 1.0. Here it is taken to 0.8. Therefore, tempering temperature is:

$$59.2=8+(27-8)\exp\left([0.8\left(T_t/917\right)^6]\right)\Rightarrow$$

T = 950 K-273 = 677˚C

It follows that there is a firm relation between the hardness after tempering and the hardness after hardening. Spies et al quantified the influence of hardness after hardening, chemical composition and tempering temperature on hardness after tempering, and developed Equation 2:

HB = 2.84H_h + 75(% C) – 0.78(% Si) + 14.25 (% Mn) + 14.77(% Cr) + 128.22(% Mo) – 54(% V) – 0.55(T_t) + 435.66(2)

Where HB is the hardness after hardening and tempering (Brinell), H_h is the hardness after hardening (HRC) and T_t is the tempering temperature (˚C).

By substitution of compositional values included in Table 1, calculated tempering temperature (~680˚C) and maximum hardness value (~60 HRC) in Equation 2, the HB will be:

HB = 270 HB

Also, according to the German standard DIN 17021 an average relation between the hardness after hardening H_h and the hardness after tempering H_t is according to Equation 3, [10]:

H_h [HRC] = (T_t/167-1.2) × H_t-17(3)

60 HRC = (680/167-1.2) × Ht – 17 $\Rightarrow$ H_t = 26 HRC

The above three relations showed a good agreement.

5.2.2. Tempering time For the tempering case, the variations of hardness and strength of rotor steel depends on the tempering temperature and holding time. The hardness decreases with increasing tempering temperature and holding time. However, the effect of tempering temperature is more significant than holding time [12].

A typical tempering curve for Cr-Mo-V rotor steel is shown in Figure 7. By using of aforementioned curve, tempering parameter developed by Larson and Miller can be predicted as follows [11]:

$$LMP = T(C + \log t) \times 10^{-3} \quad (4)$$

Where T is temperature in $^\circ$R, t is time in hr and C is a constant (C = 20).

By intersection of the maximum required hardness values (280 HB) from vertical lines and considering the predetermined tempering temperature, which is about 680°C, tempering parameter (LMP) is obtained as 35.5. So, by substitution of the known values, tempering time is calculated as follows:

$$35500 = 1716(20 + \mathrm{Log}\ t) \Rightarrow t \cong 4\text{hr}$$

The results of calculational and experimental investigations showed that, the 680°C/4hr combination is an optimum temperature and holding time in tempering heat treatment that can decrease the hardness of embrittled places while not changing the hardness of undamaged areas above acceptable limits. The tempering heat treatment procedure was carried out according to the curve in Figure 8. Heat treatment was performed by electric heating pads. Repaired areas of shafts were heat treated locally by heating a complete circumferential band located at the cater [13]. Resistant heat treatment machine with capacity of 96 kVA was used for this purpose. Practical application of tempering heat treatment has been shown in Figure 9.

The results of tempering heat treatment applied in failed section of rotor in comparison with before and after tempering, were satisfied (Figure 10).

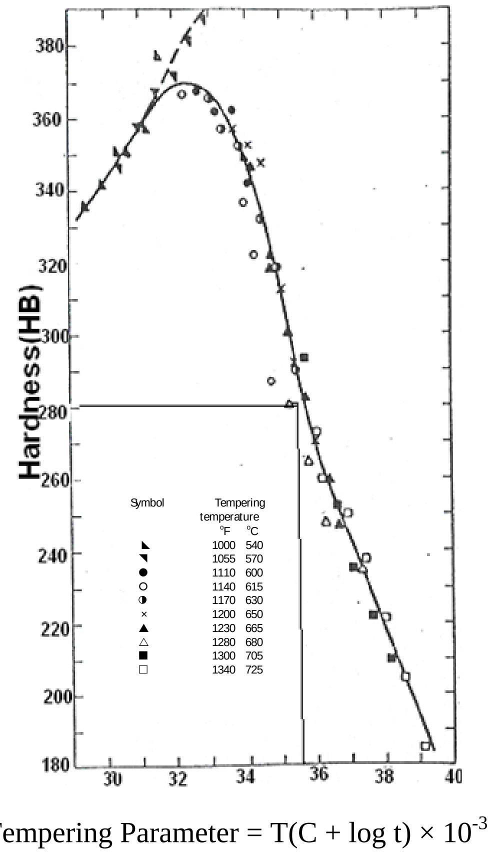

Figure 7. Tempering curve of rotor steel [11].

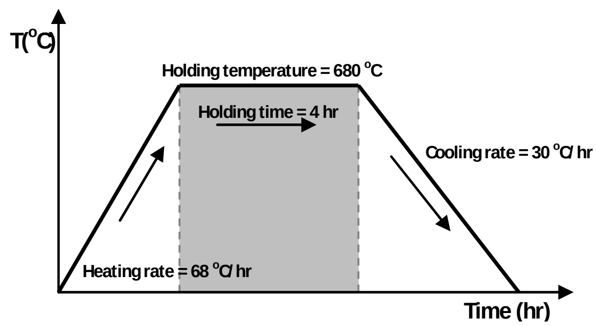

Figure 8. The tempering heat treatment procedure applied in failed section of rotor.

6. CONCLUSION

- ❖ The results of initial tests showed that the occurrence of local phase transformation (i.e. tempered bainite to austenite and finally martensite) is the main factor in local hardness increase of power plant rotor journals.
- ❖ The results of practical and experimental

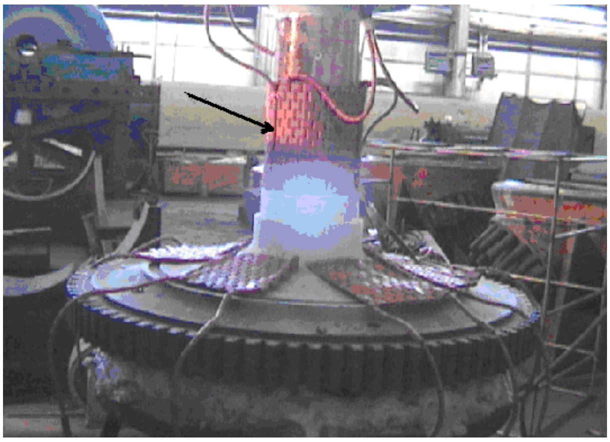

Figure 9. Practical application of tempering heat treatment procedure by using resistance method in journal area.

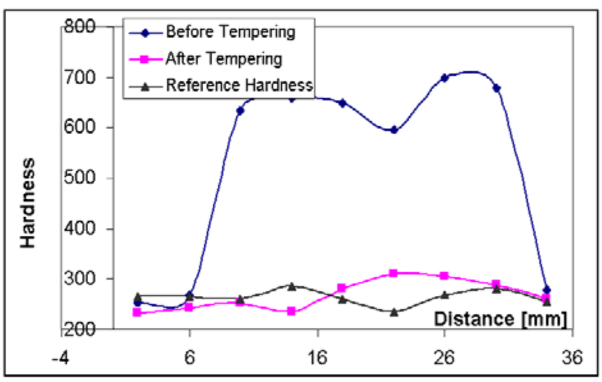

Figure 10. The results of tempering heat treatment applied in failed section of rotor with comparison to before and after tempering.

investigations showed that the 680˚C/4hr as an optimum temperature and holding time in tempering heat treatment could provide desired objectives.

7. ACKNOWLEDGEMENTS

The authors wish to thank Iran Power Plant Repair Co., Mr. Kalloti and Mr. Mohammadi for their support during the course of this work and also Mr. Alimadadi for his assistance.

8. REFERENCES

1. Mazur, Z. and Kubiak, J., "Gas Turbine Rotor Disk Repair-Case History", ***ASME Journal***, Vol. 98-GT, No. 547, (1998), 1-4.
2. Standard Specification for Vacuum-Treated Carbon and Alloy Steel Forgings for Turbine Rotors and Shaft Designation, A470-96 ASTM Standards, U.S.A., (June 1996), 258-264.
3. Jones, D. R. H., "Creep Failures of Overheated Boiler Super heater and Reformer Tubes", University of Cambridge, ***Engineering Failure Analysis***, (March 2004), 874-893.
4. Kim, G. S., Indacochea, J. E. and Spry, T. D., "Weldability Studies in Cr-Mo-V Turbine Rotor Steel", ***Proceedings of International Symposium on Welding Metallurgy of Structural Steels***, Annual Meeting of The Metallurgical Society, Inc., Denver, Colorado, U.S.A., (Febraury 22-26 1987), 79-100.
5. Sakson, I., "Electric Power Stations", Mir Publications, Moscow, Russia, (1970).
6. Gestel, R. V., "Rotor Repairs", ASME-Presented at the International Gas Turbines, Netherlands, (June 1994).
7. Brooks, C. R., "Principles of the Heat Treatment of Plain Carbon and Alloy Steels", The University of Tennessee, Knoxville, ASM International, (December 1996), 162-164.
8. ASM handbook, "Heat Treating", ***9th Ed., ASM International***, Vol. 4, (August 1991), 81-82.
9. Jaffee, R. I., "Rotor Forgings for Turbines and Generators", ***Proceedings of International workshop sponsored by Electric Power Research Institute***, Palo Alto, California, U.S.A., (September 1980).
10. Thotten, G. E. and Howes, A. H., "Steels Heat Treatment Handbook", U.S.A. International Pub, (1997), 648-652.
11. Viswanathan, R., "Damage Mechanisms and Life Assessment of High Temperature Components", ***ASM International Pub***, (1983), 275-276.
12. Lee, W-Sh. and Su, TZ-Ti., "Mechanical Properties and Microstructural Features of AISI 4340 High-Strength Alloy Steel Under Quenched and Tempered Conditions", ***Journal of Materials Processing Technology***, Vol. 87, No. 15, (Marches 1999), 198-206.
13. Defense Standard 02-304, "Shafting System and Propulsors, Requirements for Repair of Main Propulsion Shafting", Vol. 12, (September 2002).
14. Abdollah Zadeh, A., Gafari Pirlari, A. R. and Barzegari, M., "The Effect of Austenite Grain Size and Tempering Temperature on The Mechanical Properties of 1.6959 Steel Used In Pressure Vessel", ***Tenth International, Conference Pressure Vessel Technology***, Viennal, Australian, (2003), 263-268.