Available online www.jocpr.com

Journal of Chemical and Pharmaceutical Research, 2014, 6(7):1435-1439

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Nondestructive approaches for predicting the temper embrittlement of turbine rotor steel

Lv Yaling, Zhang Shenghan and Tan Yu

Environmental Science and Engineering, North China Electric Power University, Baoding, China

---

ABSTRACT

Rotor, a key component of steam turbine, has a tendency of thermal embrittlement after long-running. The severity of thermal embrittlement must be monitored timely to correct some process parameters such as warm-up time and so on to avoid further damagement. Compared with conventional destructive methods (e.g. small punch test), nondestructive approaches (e.g. chemical corrosion and electrochemical method)has drawn significant attention in predicting the material degradation in turbine rotor steels without impairing the integrity of the components. In this paper, the principle and characteristics of the nondestructive methods for predicting the temper embrittlement of turbine rotor steel were reviewed.

Key words: Temper embrittlement; turbine rotor; $FATT_{50}$; nondestructive prediction

---

INTRODUCTION

Thermal power stations provide most of the electrical energy used in China due to their low running costs, reliability, abundance of the fuel and safety. Compared to the rapid expansion of newly installed high productivity thermal power stations, there are still a considerable large number of aged thermal power plants operating in many areas. Any failures in the main components (e.g. steam turbine rotor) of these plants can cause significant costs, long downtime, and even the loss of life. Demonstrated approaches to evaluate the aging process and predict the remaining service life are highly desirable for safe operation and life extension [1].

Temper embrittlement in low alloy steels (e.g. Cr-Mo-V) of steamed turbine rotors used in thermal power plants, is one of the typical material degradations (e.g. creep, fatigue, embrittlement and corrosion) [2, 3]. The fracture appearance transition temperature, referred as $FATT_{50}$, at which the fracture surface of the material is 50% brittle or cleavage and 50% ductile, is commonly used to describe the temper embrittlement process in steamed turbine rotors [1]. Having been operated at a high temperature (>350^{o}C) for a long period of time, the turbine rotor steel will generally lose its flexibility and ductility as the segregation of metalloid impurities such as phosphorus (P), tin (Sn) and antimony (Sb), at the grain boundaries which reduces the cohesion at grain boundaries [4-6]. Among the impurity elements, phosphorus is considered as the main impurity causing temper embrittlement [5, 7, 8].

Once the temper embrittlement occurs, the resistance of the material in rotors to the embrittlement destroy will decrease and the corresponding $FATT_{50}$ value increases, indicating the turbine warming time should be prolonged to increase the rotor temperature above its $FATT_{50}$ when the turbine is cold started [5]. If the increase of $FATT_{50}$ value is not detected promptly, the rotor steel can be easily damaged or even broke, which cause severe safety accidents [4]. Therefore, it is essential to make the accurate predictions and assessments on the temper embrittlement parameters of the turbine rotor material.

To date, different destructive and nondestructive methods have been developed to detect the $FATT_{50}$ value of turbine rotors, such as small punch test [1, 9-12], electromagnetic method [13], ultrasonic [14-16], Auger electron spectroscopy [17, 18], electrochemical method [5, 19, 20] and chemical corrosion [19].

The small punch test (a miniaturized mechanical testing technique) requires a modest amount of material from the rotor surface for residual life and $FATT_{50}$ value assessment. It can provide accurate results of mechanical properties (e.g. (yield stress, tensile strength, $FATT_{50}$, fracture toughness and creep properties) from the actual components [11, 12]. Another method is to study the phosphorus grain boundary segregation on the miniature specimen using Auger electron spectroscopy, and then the phosphorus concentration at the boundary can be converted into $FATT_{50}$ value [17, 18]. Both of these two approaches are considered as destructive testing method and their application is highly-limited due to the damage on the turbine rotor.

Electromagnetic and ultrasonic methods are non-destructive, but suffer low-sensitivity and low-accuracy. Only chemical corrosion and electrochemical methods are widely used as nondestructive predicting method for the temper embrittlement properties of turbine rotor [19, 21]. The chemical corrosion method uses etch liquid (e.g. acid) to treat the rotor steel sample surface and segregation of phosphorus on steel grain boundary which leads to temper embrittlement will dissolve firstly [4]. After etch, the etch groove were measured and analyzed to predict the $FATT_{50}$ value [4]. The electrochemical method establishes dependency between the electrochemical signal and the extent of segregation of impurities (e.g. phosphorus) and can be used a nondestructive method for evaluating the temper embrittlement [5].

In this review, we summarize the recent progresses made in the area of predicting the temper embrittlement of turbine rotor steel with a focus on nondestructive approaches, including chemical corrosion and electrochemical methods.

CHEMICAL CORROSION METHOD

Intergranular corrosion (IGC) is a form of corrosion where the boundaries of crystallites of the material are more susceptible to corrosion than their insides [22]. In austenitic stainless steels, where chromium is added for corrosion-inhibiting element, chromium carbide precipitates at the grain boundaries, resulting in the formation of chromium-depleted zones adjacent to the grain boundaries which is vulnerable to corrosion [23, 24]. The chromium concentration in chromium-depleted zones is significantly lower than that in the passivation zones, and these zones also act as local galvanic couples, causing local galvanic corrosion. The phosphorus segregation on the grain boundary which will lead to temper embrittlement is also correlated to intergranular corrosion [25, 26]. The composition of different elements (such as carbon, chromium, nickel, phosphorus, tin and antimony) determines the tendency of intergranular corrosion in austenitic stainless steel materials.

The fracture appearance transition temperature, referred as $FATT_{50}$, which is used to describe temper embrittlement properties of the material, will be obviously influenced by various parameters, such as the temperature of corrosion liquids, grain size, the content of alloy element Cr and impurity elements [4, 27]. Kadoya et al. found that P-doped steels showed evident embrittlement by the segregation of P at grin boundaries, whilst the Sn-doped steels showed little embrittlement [20]. Chemical etching test was used to measure the embrittlement and the correlation between width W of etched grain boundary and FATT was recognized. Multiple regression was conducted to express FATT using W and other variables as a nondestructive measurement [20]: $FATT = 99.12 \cdot W + 1.609 \cdot Hv + 816.4 \cdot Si - 652.5 \cdot Mn + 3320 \cdot P - 310.4 \cdot Cr + 3404 \cdot Sn - 0.282 \cdot J\text{-factor} + 325.6$, where Hv is the Vickers hardness, J-factor is $(P + Sn) \cdot (Si + Mn) \cdot 10^4$. A regression equation which can estimate the actual FATT with the scatter of $\pm 20^oC$ was obtained [20].

Chen et al. used picric acid and sodium dodecyl benzene sulfonate solutions to corrode the turbine rotor steel sample [4, 27, 28]. Phosphorus on grain boundary dissolves firstly, and width of etch groove on the grain boundary were measured and analyzed by Photoshop. Due to phosphor's prior dissolve which leads to the grain boundary corrosion, FATT of rotor steel relate with concentration of element phosphorus (C_P) in the grain boundary, and C_P in the grain boundary related with the steel sample's degree of corrosion in the particular etching solution. The width of grain boundary increase with the FATT, and this trend becomes more obvious as the temperature raises. The predict model of FATT was established by make multiple linear regression analysis on all relevant parameters [4, 27], and expresses as $FATT = 263.725 - 0.981 \cdot T + 322.141 \cdot w + 10621.77 \cdot C_S + 0.119 \cdot J - 16.664 \cdot N$. where T is temperature, w is the width of grain boundary, Cs is the concentration of impurity element S, J is Chemical content parameter ($J = (C_{Si} + C_{Mn}) \cdot (C_p + C_{Sn})$), and N is the grain size. The verifying experiment show that the model's error range is within $\pm 20^oC$ [4, 27].

Chen et al. developed a new etch solution using nitric acid and acetic acid mixture to corrode the steam rotor steel [29]. The relationship between width of etch groove, $FATT_{50}$ and other parameters were established using multiple linear regression analysis: $FATT_{50} = -227 + 375 \cdot W - 0.258 \cdot Hv + 141 \cdot C_{Cr} + 5334 \cdot Cs - 256 \cdot R + 0.146 \cdot J - 8.73 \cdot N$, where correlation parameter R = (C_c + C_{Mo})·(C_{Si} - C_V). The result showed that the error between prediction values and actual values is in the range of ±15°C [29].

ELECTROCHEMICAL METHOD

As a relatively high-precision nondestructive detecting method, electrochemical approach has drawn significant attention in predicting the material degradation in turbine rotor steels without impairing the integrity of the components.

Mao et al. investigated the electrochemical behaviors of type 321 austenitic stainless steel in sulfuric acid solution, found that the electrochemical polarization curves can be used to estimate the aging embrittlement degradation [30]. Kwon et al. studied the effect of thermal aging on mechanical and electrochemical behavior of pristine and degraded Cr-Mo-V alloys [31]. The electrochemical corrosion characteristics were investigated by the potentiodynamic anodic polarization and the reactivation methods in an 50 wt% $Ca(NO_3)_2$ electrolyte, and the electrochemical characteristic values showed a good correlation with the rate of material degradation obtained from destructive testing [31].

Komazaki et al. developed a methodology for thermal aging embrittlement and creep damage evaluation of W alloyed 9% Cr ferritic steel [32-34]. Results on electrochemical polarization measurements in 1N KOH solution revealed that the peak current density ‘Ip’ increased with thermal aging and creep damage and reflected not only the thermal effect but also the stress effect on creep damage [32]. The Ip value corresponded to the selective dissolution volume of precipitates ($M_{23}C_6$ and Laves phase) and the increase in the Ip indicates the increase in amount of chromium precipitated as Laves phase [32]. The ‘Ip’ value was found to be increasing linearly with the degree of embrittlement as evaluated by impact absorbed energy at 0°C [33, 34].

For the purpose of non-destructive evaluation of the degree of temper embrittlement in 2.25wt%Cr-1wt%Mo steels, anodic and single loop electrochemical potentiokinetic reactivation (SL-EPR) polarization curves of the embrittled specimens which had been serviced for oil refinery reactor for the maximum 25 years have been measured in 55 wt% $Ca(NO_3)_2$ solution at 30°C [35]. Difference in current density (IP2-E-Ipass-E) between active second peak and passive in an anodic polarization curve of temper-embrittled specimens increases linearly with increase in FATT in the range of mode transfer over transgranular cleavage to intergranular of Charpy impact fracture [35].

Zhang et al. claimed that the prediction accuracy for FATT by this multiple linear regression technique may not sufficient for the life assessing of the turbine rotor, which may due to the pre-determined prediction model is too simple and the prespecified size and shape of the model are not adequate for the complex relationships between FATT and its parameters [5, 36]. They developed a genetic programming (GP) for $FATT_{50}$ prediction where the structures subject to adaptation are the hierarchically organized computer programs whose sizes and forms dynamically change during simulated evolution [5, 37-39]. Single loop electrochemical polarization reactivation (EPR) test was carried out in 0.1M sodium molybdate electrolyte at different temperature.

The generative method for the initial random population was ramped half-and-half [37] and the fitness measure of each population was defined as the mean square error (MSE) as follows: $\emptyset = \frac{1}{N}\sum_{i=1}^{N}(q_{pre,i} - q_{exp,i}\ )^2$, where q_{pre} and q_{exp} are prediction value and experimental value, respectively [5]. The set of function genes F was defined as F = {+, -, *, /, sin, cos, log, exp}, and the set of terminal genes T included the independent variables {II, T, J, N, Cr, S, Hv} and random floating-point constants [5]. With the genes, the simulated evolution produced the best model for prediction of temper embrittlement is: $FATT_{50} = \frac{(x_2+6.095)\cos(x_6)}{0.437x_5+\cos(x_5)} - \frac{(x_6-x_7)x_5}{x_4} - 2\cos(x_5+x_6) + \log(x_1x_3^2x_7) + 67.516$, where x_l = T, x_2 = I, x_3 = J, x_4 = N, x_5 = Cr, x_6 = S, x_7 = H_v, repectively. The multiple correlation coefficient between predicted and measured $FATT_{50}$ was 0.990, indicating the model obtained by GP can be used in predicting temper embrittlement of new rotor materials with a precision of about ±20 °C [5].

Then the similar genetic programming approach was used by Zhang et al. and peak current density of reactivation measured by the potentiodynamic anode polarization method, temperature of electrolyte, the chemical composition of steel (J-factor), Cr content and the grain size of steel were used as independent variables, while $FATT_{50}$ was used as dependent variable. The accuracy of this model was found better than that of the model obtained using multiple linear regression method [40]. Later, Cao et al. used hardness as the new independent variables to improve the existing genetic programming approach [41]. The prediction error of the model is within the scatter of ±20°C, indicating the prediction model obtained by genetic programming is feasible and effective [41].

Bayesian neural network was proposed to modelling the temper embrittlement of steam turbine rotor in service, and the $FATT_{50}$ was predicted as a function of ratio of the two peak current densities (I_p/I_{pr}) tested by electrochemical potentiodynamic reaction method [42]. The Bayesian approach involves the optimization of the objective function

$S_{(w)}$ that comprises the conventional sum squared error function E_D as well as an additional weight error term E_w, which is to penalize the more complex weight function in favor of simpler functions [42-46]. The neural network showed a more precise prediction of temper embrittlement of rotor steels than the prediction using multiple linear regression. The training error and verifying error is with the scatter of ±20°C [42].

CONCLUSION

$FATT_{50}$ is a key indicator in detecting the severity of thermal embrittlement. For the turbine rotor, this indicator could be monitored by nondestructive methods timely to correct process parameters, including chemical corrosion and electrochemical approaches. Compared with conventional destructive methods, these approaches are low-cost, easy to operate, with reasonable sensitivity and accuracy. However the predicted results are still needed to be verified by small punch or Charpy impact tests. Future development on these nondestructive methods may require more variables to be considered in the model which can further improve the accuracy of the prediction of $FATT_{50}$.

Acknowledgments
The paper was supported by 'the Fundamental Research Funds for the Central Universities'(NO.13MS85).

REFERENCES

[1] Ha J.S., E. Fleury, *International Journal of Pressure Vessels and Piping*, vol.75, no.9, pp.707-713, **1998**.
[2] Kadoya Y., T. Goto, M. Takei, N. Karuki, T. Ikuno, Y. Nishimura, *Transactions of the Japan Society of Mechanical Engineers Series A*, vol.57, no.537, pp.1085-1090, **1991**.
[3] Uemura H., M. Kohno, *Tetsu-To-Hagane/Journal of the Iron and Steel Institute of Japan*, vol.93, no.4, pp.324-329, **2007**.
[4] Chen Y.M., Y. Long, Z.G. Han, Y.H. Wang, in: Asia-Pacific Power and Energy Engineering Conference, Wuhan, **2009**.
[5] Zhang S.H., Y.Z. Fan, Y.M. Chen, S.L. Zhou, in: International Conference on Industrial Technology, Hong Kong, **2005**, pp. 768-771.
[6] Fujita A., M. Shinohara, H. Yokota, K. Kaku, K. Soeda, Y. Kuroda, *Tetsu-To-Hagane/Journal of the Iron and Steel Institute of Japan*, vol.84, no.3, pp.236-241, **1998**.
[7] Kameda J., R. Ranjan, *Acta Metallurgica*, vol.35, no.7, pp.1515-1526, **1987**.
[8] Kameda J., R. Ranjan, *Acta Metallurgica*, vol.35, no.7, pp.1527-1531, **1987**.
[9] Shekhter A., S. Kim, D.G. Carr, A.B.L. Croker, S.P. Ringer, *International Journal of Pressure Vessels and Piping*, vol.79, no.8-10, pp.611-615, **2002**.
[10] Komazaki S.I., T. Shoji, K. Takamura, *Journal of Engineering Materials and Technology, Transactions of the ASME*, vol.127, no.4, pp.476-482, **2005**.
[11] Turba K., R.C. Hurst, P. Hähner, *Journal of Nuclear Materials*, vol.428, no.1-3, pp.76-81, **2012**.
[12] Mao X., T. Shoji, H. Takahashi, *Journal of Testing and Evaluation*, vol.15, no.1, pp.30-37, **1987**.
[13] Dobmann G., *International Journal of Materials and Product Technology*, vol.26, no.1-2, pp.122-139, **2006**.
[14] Jeong H., S.H. Nahm, K.Y. Jhang, Y.H. Nam, *KSME International Journal*, vol.16, no.2, pp.147-154, **2002**.
[15] Jeong H., S.H. Nahm, K.Y. Jhang, Y.H. Nam, *Ultrasonics*, vol.41, no.7, pp.543-549, **2003**.
[16] Hsu C.H., H.Y. Teng, S.C. Chiu, *Materials Transactions*, vol.44, no.11, pp.2363-2368, **2003**.
[17] Ding R., A. Islam, S. Wu, J. Knott, *Materials Science and Technology*, vol.21, no.4, pp.467-475, **2005**.
[18] Song S.H., J. Wu, L.Q. Weng, T.H. Xi, *Materials Science and Engineering A*, vol.520, no.1-2, pp.97-100, **2009**.
[19] Fan Y.Z., Y.M. Chen, S.H. Zhang, *Turbine Technology*, vol.no.2, pp.100125884, **2004**.
[20] Kadoya Y., T. Goto, M. Takei, N. Haruki, K. Ikuno, Y. Nishimura, *American Society of Mechanical Engineers, Power Division (Publication) PWR*, vol.13, no.pp.229-234, **1991**.
[21] Viswanathan R., S.M. Bruemmer, R.H. Richman, *Journal of Engineering Materials and Technology, Transactions of the ASME*, vol.110, no.4, pp.313-318, **1988**.
[22] Kasparova O.V., *Protection of Metals*, vol.40, no.5, pp.425-431, **2004**.
[23] Stratulat A., J.A. Duff, T.J. Marrow, *Corrosion Science*, vol.no.**2014**.
[24] La Fontaine A., H.W. Yen, P. Trimby, S. Moody, S. Miller, M. Chensee, S. Ringer, J. Cairney, *Corrosion Science*, vol.no.**2014**.
[25] Bruemmer S.M., *Corrosion*, vol.42, no.3, pp.180-185, **1986**.
[26] Fan Y., X. Zhai, R. Ma, A. Du, *Turbine Technology*, vol.50, no.4, pp.318-320, **2008**.
[27] Chen Y.M., Y.H. Wang, X.Y. Li, S.H. Zhang, *Turbine Technology*, vol.50, no.1, pp.74-77, **2008**.
[28] Chen Y.M., Y.H. Wang, S.H. Zhang, *Thermal Power Generation*, vol.10, no.pp.18-21, **2007**.
[29] Chen Y.M., Y. Long, Z.G. Han, S.H. Zhang, *Turbine Technology*, vol.51, no.6, pp.471-477, **2009**.
[30] Mao X., W. Zhao, *Corrosion*, vol.49, no.4, pp.335-342, **1993**.
[31] Kwon I.H., S.S. Baek, H.S. Yu, *International Journal of Pressure Vessels and Piping*, vol.80, no.3, pp.157-165,

2003.
[32] Komazaki S., S. Kishi, T. Shoji, K. Higuchi, K. Suzuki, *Zairyo/Journal of the Society of Materials Science, Japan*, vol.50, no.5, pp.503-509, **2001**.
[33] Komazaki S.I., S. Kishi, T. Shoji, H. Chiba, K. Suzuki, *Materials Science Research International*, vol.9, no.1, pp.42-49, **2003**.
[34] Komazaki S.I., S. Kishi, T. Shoji, H. Chiba, K. Suzuki, *Zairyo/Journal of the Society of Materials Science, Japan*, vol.49, no.8, pp.919-926, **2000**.
[35] Shibuya T., T. Misawa, *Zairyo to Kankyo/ Corrosion Engineering*, vol.48, no.3, pp.146-154, **1999**.
[36] Zhang S., Y. Fan, Y. Chen, *Jixie Gongcheng Xuebao/Chinese Journal of Mechanical Engineering*, vol.43, no.10, pp.211-214, **2007**.
[37] Brezocnik M., L. Gusel, *International Journal of Advanced Manufacturing Technology*, vol.23, no.7-8, pp.467-474, **2004**.
[38] Brezocnik M., M. Kovacic, M. Ficko, *Journal of Materials Processing Technology*, vol.157-158, no.SPEC. ISS., pp.28-36, **2004**.
[39] Lee D.G., H.G. Kim, W.P. Baek, S.H. Chang, *International Communications in Heat and Mass Transfer*, vol.24, no.7, pp.919-929, **1997**.
[40] Zhang S.H., Y.Z. Fan, Y.M. Chen, X.Y. Li, *Kang T'ieh/Iron and Steel (Peking)*, vol.41, no.5, pp.69-72+77, **2006**.
[41] Cao X., Y. Fan, R. Ma, A. Du, *Journal of Computational and Theoretical Nanoscience*, vol.5, no.8, pp.1713-1716, **2008**.
[42] Zhang S.H., Y.Z. Fan, Y.M. Chen, in: International Conference on Industrial Technology, Hong Kong, **2005**, pp. 991-994.
[43] Kelemen A., Y. Liang, in: Proceedings of the International Joint Conference on Neural Networks, **2003**, pp. 654-659.
[44] Danaher S., S. Datta, I. Waddle, P. Hackney, *Wear*, vol.256, no.9-10, pp.879-888, **2004**.
[45] Edwards D.C., C.E. Metz, R.M. Nishikawa, in: Proceedings of SPIE - The International Society for Optical Engineering, **2002**, pp. 1-12.
[46] Chua C.G., A.T.C. Goh, *International Journal for Numerical and Analytical Methods in Geomechanics*, vol.27, no.8, pp.651-667, **2003**.