HIGH TEMPERATURE FATIGUE DAMAGE EVALUATION OF STEAM TURBINE ROTOR STEEL

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High temperature fatigue damage of heat relief grooves of HP rotor can be assessed by measurement of residual stresses present in the surface of the component. These stresses get accumulated in the surface due to cyclic operations such as start-up, shut downs and load transients. Changes in the residual stress values were examined in the laboratory by using X-ray residual stress measurements for Cr-Mo-V rotor steel specimens subjected to high temperature low cycle fatigue in order to develop a method for non-destructive damage detection. A linear variation of residual stress with fatigue cycles was observed. The method has been applied on a 62.5MW steam turbine operated for 1,56,456hrs to assess the fatigue damage.

INTRODUCTION

The effective maintenance based on the future life assessment becomes a matter of primary concern in the electric utility industries to insure operational reliability, as older fossil power plants are increasing in number. Since the calculation method of the life (crack initiation) prediction has a limit in its reliability, the application of non-destructive examination is recognized to be important. This paper describes a method based on X-ray residual stress measurement for evaluating non-destructively the fatigue damage of high-temperature steam turbine rotors.

Experience shows that fatigue crack initiation usually results from localized stress (and strain) concentration in small areas close to external surfaces. The initiation stage may also represent major fraction of a part's life

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span and the damaged area of the part at this stage is small (0.1 to 3mm thickness). However, following initiation, crack propagation is comparatively very rapid and quickly results in widespread damage that necessitates replacement of the part. Under these conditions it is possible to give a part a new lease of life by removing the small damaged area and without impairing the parts' operational capability. Therefore research efforts are directed to develop non-destructive evaluation method to assess high temperature fatigue damage before crack initiation.

Most low-cycle fatigue problems in steam turbine involve thermal as well as mechanical loadings, due to start-up, shut-downs and load transients. Constraint of thermal expansion causes thermal stresses which may eventually initiate and propagate fatigue cracks. Heating and cooling of the surface of a thick structure leads to a hysterisis loop as shown in Fig.1 (1). It is to be noted that as the temperature gradient reduces, the strain becomes zero leaving tensile residual stress at surface, the point R in the figure. During the following period of steady running at 550°C, the residual tensile stress at the surface, is able to relax from R to R′ but not significantly.

Residual stress may be defined as those stresses present in a material without any application of external forces or moments. Machining operation will give rise to compressive residual stress at the surface. With the increasing number of cyclic operations, initial compressive residual stress gradually changes to tensile residual stress leading to crack initiation at the surface. Residual stress varies with accumulated strain (2) and hence suitable for fatigue damage assessment. In fact all the recent non-destructive fatigue damage assessment systems such as Barkhausen noise, acousto-velocity method, X-ray diffraction, are based on residual stress measurement.

Changes in the residual stress values were examined in the laboratory by using X-ray residual stress measurement for Cr-Mo-V rotor steel specimens subjected to high temperature low cycle fatigue (LCF) in order to develop a method for non-destructive damage detection and non-destructive remaining life prediction of a component. The measurement were also carried out on a 62.5MW steam turbine operated for 1,56,456hrs for evaluation of the associated fatigue damage.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used in the study was a rotor steel forging and is as per 28 CrMoV 5 9 specification. High temperature LCF testing was carried out as per ASTM E606 standard on MTS 25 Ton servo-hydraulic machine and high temperature quartz rod extensometer was used to measure the strain. The induction heating system was used for maintaining the temperature at 540ºC and a frequency of testing was 0.05Hz with sine wave form. The specimens were tested at total strain ranges of 1.7%, 1.3%, 0.75% and 0.6%. Tests were interrupted at periodic intervals during testing to measure residual stress. Residual stresses were measured using Rigaku X-ray residual stress analyzer. Fig.2 shows residual stress variation with number of cycles during the low cycle fatigue testing. Table I lists % total strain versus number of cycles to failure.

Table.I
LCF data on forging

% Total strain	Cycles to failure
1.70	465
1.30	948
0.75	2340
0.60	3737

RESULTS AND DISCUSSION:

Low Cycle Fatigue Testing

The LCF data as given in Table I are in agreement with those reported by Kuwabara et al(3). It was reported (1) that for life estimation of ½CrMoV casting steel, isothermal data at maximum operating temperature can be used instead of thermo-mechanical fatigue (TMF) values as isothermal values are conservative. Ewald et al (4) mentioned that endurance for the out of cycle TMF testing was much more than the isothermal data. In our earlier work (5), it was noticed that TMF (300-550°C) life for CrMoV steel to be more than LCF life at 540°C. Therefore LCF values at 540°C can be used for life calculation.

Correlation of Residual Stress with Low Cycle Fatigue Life

It is evident from Fig.2 that initial compressive stress values decreases with number of cycles and after reaching a tensile value the failure of the specimen occured.

It is generally accepted that fatigue strength is significantly increased by compressive residual stress and a gradual reduction in compressive stress with cycles is observed (6). Also tensile stress has deleterious effect on fatigue life. Taira et al(7) observed that residual stress forms in annealed specimens due to elongation of the near surface region from excess vacancies formed during cycling. This continues until work hardening, at which time maximum compressive stress occurs. Additional cycling produces deformation of deep layers resulting in decrease in compressive stress. In case of machined component, it has already been subjected to working and hence would have maximum compressive stress. Further cycling operation produces softening i.e reduction in compressive stress. It was well established(8) that gradual decrease in fatigue life is known to occur at or near the fatigue limit. Well above this region or in the low cycle fatigue region, the residual stress state depend on the magnitude of loading. The application of residual stress technique to fatigue damage depends on the stability of the residual stress present. According to Skeleton(1), relaxation of residual stress during continuous operation at 550°C is not significant for a Cr-Mo-V steel (Fig.1) and hence it is reasonable to assume that accumulation of tensile residual stress takes place on the surface of the rotor for each cycle of start up and shut down.

Quantitative relations based on a linear proportionality between residual stress and logarithmic cycles for high cycle fatigue have been empirically established (9-11). Neff(12) and Ohuchida et al(13) reported similar relationship during high cycle fatigue testing. Hitachi has already introduced fatigue damage evaluation system for boiler feed pump shaft based on linear relationship between residual stress and life consumption ratio, using X-ray diffraction technique method(14). Also our own studies (15) relating to fatigue damage assessment of boiler feed water pump shaft show the utility of X-ray diffraction technique for fatigue life assessment.

Present results show a linear variation of residual stress with number of cycles during LCF testing for all the strain levels. Slopes of residual stress versus number of cycles (dR/dN) are obtained for each strain level. Its variation with strain is shown in Fig.3. The above data can be used for assessing the high temperature damage in CrMoV steel.

APPLICATION OF RESIDUAL STRESS MEASUREMENT

Residual stress measurements were made on the 62.5 MW steam turbine rotor operated for 1,56,456 hours using Rigaku X-ray stress analyzer.

Measurements were carried out on the heat relief grooves at four clock positions corresponding to the hole nos.1,4,7 and 10 of the generator coupling flange. The measurement direction in all cases were longitudinal. The damage due to thermal fatigue is known to be most severe at the steam entry point near the curtis wheel where the temperataure is maximum. Since it was not possible to experimentally measure the values close to the curtis wheel, residual stress measurements were made at a distances of 90,130,160,210, 270 and 330mm away from the curtis wheel towards the journal. The measured values were extropolated to determine the approximate stess value at the curtis wheel. The values of residual stress obtained in the case of hole no.4 is given in Fig.4. It is evident from the Fig.4 that away from curtis wheel residual stresses are more compressive of the order of 15Kg/sqmm, whereas very close to curtis wheel the residual stresses are close to zero. Based on the laboratory results, this location appears to have been subjected to higher degree of thermal fatigue damage among all other locations examined.

CONCLUSIONS

A methodology based on variation of residual stress with fatigue cycles for CrMoV rotor steel was developed using X-ray diffraction technique. This method was applied to actual component to assess the fatigue damage.

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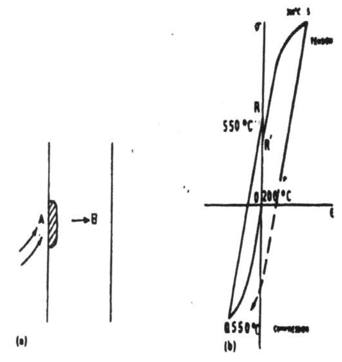

Fig.1 Hysterisis Loop

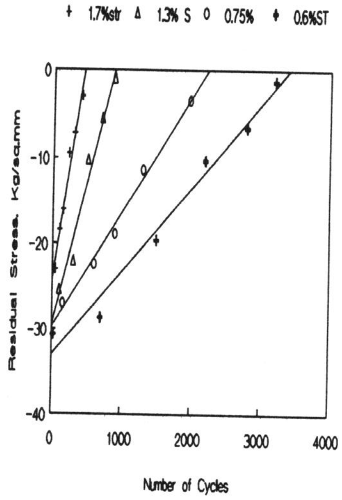

Fig.2 Residual stress vs. Number of cycles during LCF testing

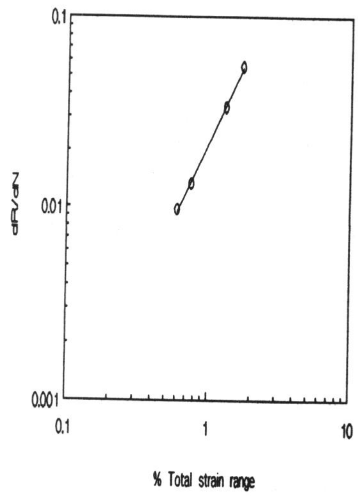

Fig.3 Plot of dR/dN Vs. $\%\Delta\epsilon_t$

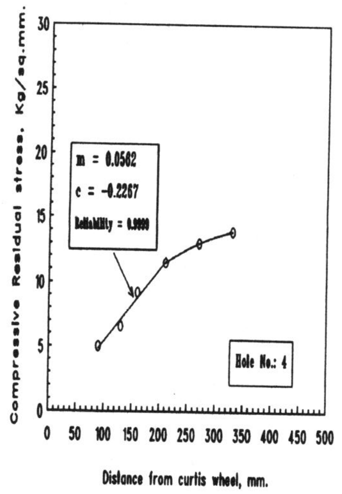

Fig.4 Variation of residual stress away from the curtis wheel