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Damage Assessment of Process Heater Tube by Magnetic Technique : A Case Study

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ABSTRACT

Ferromagnetic properties of steel change with the microstructure, composition and the stress state of the materials. Such variations are also taking place when the steel components are in service. Hence magnetic techniques may be used as a potential tool for integrity assessment of engineering components. The present work deals with the magnetic characterisation of process heater tube made of austenitic steel HP-40 grade employed in naphtha cracking unit of a petrochemical industry. The tube was non-magnetic in the virgin state and became magnetic during service exposure. The origin of magnetism in service exposed tube will be discussed here. Feasibility of using magnetic non-destructive evaluation technique for damage assessment of the studied process heater tube will also be explored in the present investigation.

INTRODUCTION

The process heater tubes are used in the petrochemical industries for processing hydrocarbons at high temperature and pressure. During this processing carbons are coming out from the process fluid and deposited at the inner wall. The deposited carbon interacts with the alloying elements of the process heater tube and changes the microstructure and the composition of the alloy [1-2]. The alteration of microstructure and composition change the design life of the tube. As the magnetic properties also vary with the microstructure and composition of the materials [3-5], the magnetic technique has been used in the present study for the damage assessment of in-service process heater tube. In the present case, the process heater tubes are the radiant coils of hydro-cracker unit of a petrochemical industry in India.

PLANT HISTORY

Radiant coils under study were used to crack naphtha into ethylene and other bye products by pyrolysis. Coils were suspended vertically in the radiant zone of furnace. During the process of cracking naphtha coke layer formed and the metal wall temperature raised to maintain the temperature for cracking naphtha to a specified limit. When the metal wall temperature reached 1100 °C the unit automatically switched through the decoking cycle. In this cycle a mixture of steam and air passes through the tube at 960 °C. After decoking operation the unit automatically reverts back to its normal cycle.

MATERIALS

The radiant coil on which the present study has been conducted is made of modified HP40 which contains 35Ni, 25Cr, 1Nb, 0.3C in its virgin state. The tube is manufactured by centrifugal casting. High rpm ensures defect free casting. A thin layer at the internal surface is removed by honing to make the surface smooth which inhibits coke deposition. The design life of the tube is 11 years. However, failure observed after 3-4 years of service. In the present study two tubes are investigated which were in service for (a) two years and (b) two and half years.

CAUSE OF DAMAGE

The design life of the tube was estimated primarily using their high temperature rapture strength data. However during service as radiant coil for naphtha cracking several additional damage mechanisms are taking place that are not included in the design life calculation. In the process of cracking hydrocarbon coke deposit inside the tube which is burned away by passing steam and air mixture. The maximum temperature and pressure that the radiant coils experienced are 1100 °C and 1 MPa. During the entire operation, carburisation from the inside surface takes place which reacts with various alloying elements. Due to high temperature operation, oxidisation from outside surface also takes place. The carburisation and oxidation change the microstructure as well as composition at the near surface zone and reduces the life of the tube. Besides carburisation and oxidation, service exposed tube also experiences creep damage, thermal stress, thermal fatigue etc.

DAMAGE CHARACTERISATION

Ultrasonic examination and radiography are used to detect crack initiation due to thermal fatigue or thermal stress. Dimension measurement gives an idea of the erosion. However, an unique property in the service exposed materials are observed that they become ferromagnetic after certain period of service although the virgin material is non magnetic. Hence, attempt has been made to use ferromagnetic properties of service exposed material as a tool for damage assessment of radiant coil. Microstructural characterisation was also carried out to correlate the magnetic properties with the structural change.

MICROSTRUCTURAL CHARACTERISATION

Optical micrograph of the outer and inner surface of a tube which was in service for two years is shown in Fig. 1. It shows the grain boundary carbide free region from the edge of inner (150μm) as well as outer (250μm) wall to the inside of the tube. SEM-EDAX analysis revealed that the grain boundary Cr-rich carbides (Cr_3C_7) of the virgin sample transformed to coarser carbides ($Cr_{23}C_6$) after service exposure. Chromium depleted regions also detected by EDAX at inner and outer edges of the service exposed tube. It was found that the Cr-concentration at the outer most layer dropped to 11% whereas the inner most layer became 19% for two years service exposed tube.

After two and half years of service exposure the Cr-depletion in both inner and outer most layers became close to 8%.

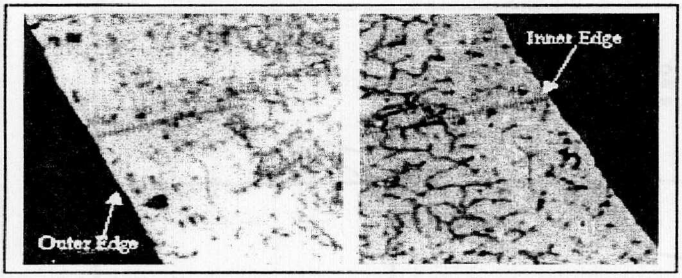

Fig. 1: Optical micrograph showing the microstructure of outer and inner surface of the service exposed tube

In service exposed tube, the oxides at the outer surface was formed due to the exposure of the tube in air at high temperature (>1100 °C). The formation of Cr oxides decreased the Cr content at the outer layer of the tube and dissolution of carbides took place, which led to the grain boundary carbides free region near the outer surface. At the inner surface the diffused carbon from the naphtha cracking interact with the chromium and formed carbides and grew with the grain boundary carbides. After reaching a critical size, the carbide came out from the surface as a metal dusting. The metal dusting and depletion of Cr led to the dissolution of near by carbides at the inner surface of the tube, which resulted to grain boundary carbide free region. Thus the oxidation at the outer surface and carburisation at the inner surface led the Cr depletion region near both the surface. The higher depletion of Cr at the outer surface of two years exposed tube suggested that the oxidation process was predominant compared to the carburisation process at the beginning. However, after certain exposure time, oxidation process slowed down as observed in two and half years exposed tube.

Evaluation of Magnetic Properties

The virgin tube was non-magnetic. Hence magnetic properties were evaluated only on service exposed tubes and these were carried out both by destructive and non-destructive ways. Two service exposed tubes were taken for this study. The tubes were in service for (a) 2 years and (b) for 2 ½ years. Magnetic hysteresis loops were taken on the toroidal samples cut from the service exposed tubes. The hysteresis loop for the two service exposed specimens are shown in Fig. 2(a) and (b) respectively. The magnetic parameters obtained from the measurements are shown in the Table 1. It is clear from the Table 1 that all hysteresis loop parameters changed with the exposure time. Hysteresis loop was also measured by removing 1mm outer surface layer and no measurable hysteresis loop was observed for two years exposed tube indicating that only the outer surface layer was magnetic at the measured exposure value. However, hysteresis loop was observed when 1mm from the outer layer was removed from two and half years exposed tube. Fig. 3 shows the hysteresis loop when 1mm from the outer surface is removed from two and half years exposed tube.

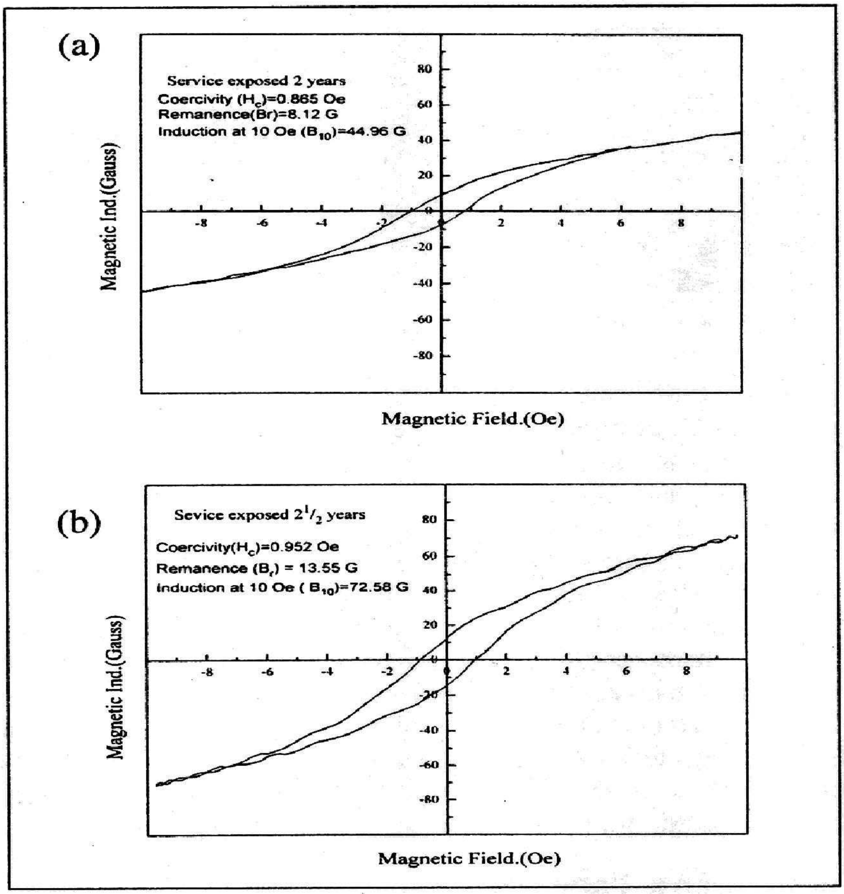

Fig. 2: Hysteresis loop of service exposed tubes. Tubes were service exposed for (a) 2 years and (b) 2 ½ years.

Table 1: Magnetic properties of the exposed tubes

Properties	*Exposed for 2 years*	*Exposed for 2.5 years*
Initial permeability (μ_i)	6.9	10.51
Coercivity (H_c)	0.87 Oe	0.95 Oe
Remanence (B_r)	8.12 G	13.55 G
Inductance at 10 Oe (B_{10})	44.96 G	72.58 G

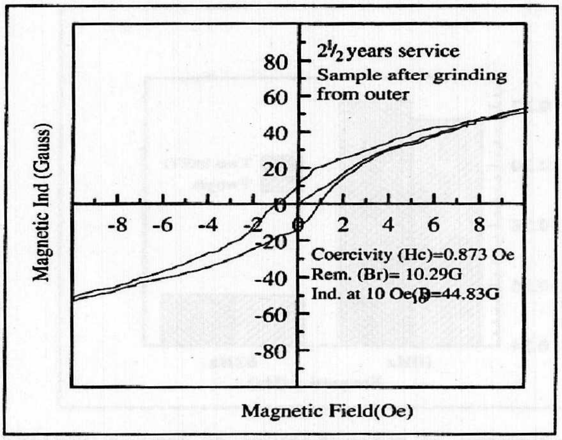

Fig.3: Hysteresis loop of 2 ½ years service exposed tube after removing 1mm outer layer.

Magnetic induction was also evaluated by non-destructive testing at different frequencies using a specially designed NDT probe developed at the National Metallurgical Laboratory. The output signal of the probe gives the magnetisation level of the test materials. The result is shown in Fig. 4. The main purpose of this experiment is to see variation of magnetisation at different depth. It may be mentioned that at low frequency the depth of penetration of magnetic field is high. Exponential decay of the magnetisation level with frequency suggested that magnetisation value decreased from outside to inside layer. Fig. 5 shows the variation of magnetisation value for the two service exposed tubes at two different frequencies determined by specially designed NDT probe developed at the National Metallurgical Laboratory. At low frequency, 10Hz, where depth of penetration was more, small increase in magnetisation level was observed in two and half years service exposed tube whereas at high frequency (62 Hz), which gives only surface magnetisation value, no variation between the two tubes was observed.

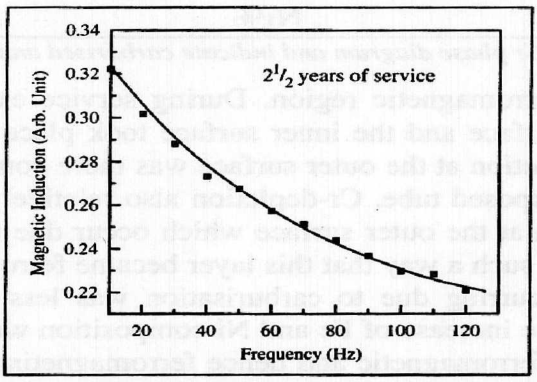

Fig. 4.: Frequency variation of magnetisation for 2½ years service exposed tube

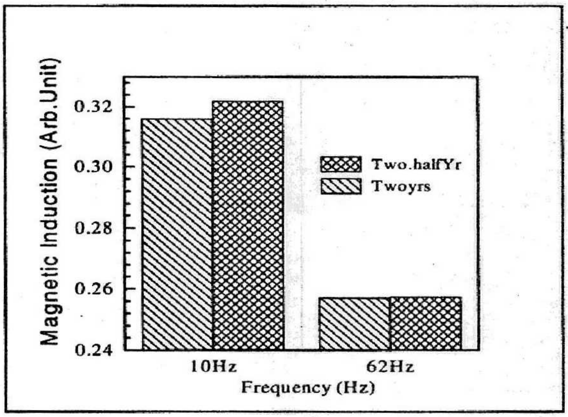

Fig.5: Comparison of magnetisation of service exposed tubes at two magnetisation frequency

ORIGIN OF MAGNETISM IN SERVICE EXPOSED TUBE

To understand the origin of magnetism, it is necessary to look the Fe-Ni-Cr phase diagram which is shown in Fig. 6. Fe, Ni and Cr composition at the virgin state were

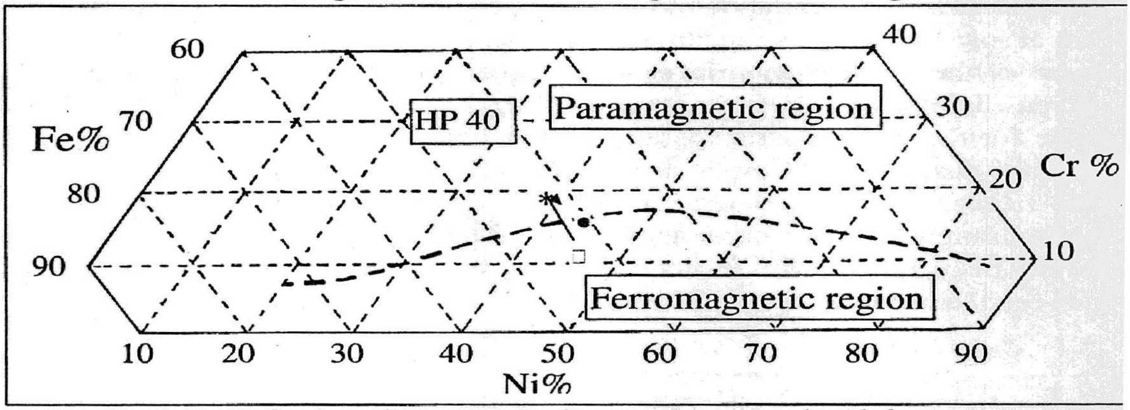

Fig. 6: Fe-Ni-Cr phase diagram and indicate carburised and oxide layer.

such that it is in the ferromagnetic region. During service exposure, compositional variation at the outer surface and the inner surface took place as observed by SEM-EDAX analysis. Cr-depletion at the outer surface was more compared to the inner one for 2 years of service exposed tube. Cr-depletion also relatively increased the Fe and Ni content. Cr-depletion at the outer surface which occur due to oxidation, increased the Fe and Ni content in such a way that this layer became ferromagnetic. Cr-depletion at the inner surface occurring due to carburisation was less for two years service exposed tube and relative increase of Fe and Ni composition was still not sufficient to make the inner surface ferromagnetic and hence ferromagnetism was not observed by removing 1mm outer surface of the tube. However, in two and half years service exposed tube Cr-depletion in inner and outer surface was almost similar which resulted both the surface ferromagnetic. The observed variation of magnetisation measurement at low frequency by NDT technique for the two measured samples suggested that carburisation depth could be measured by the developed nondestructive magnetic technique.

CONCLUSION

Magnetic hysteresis loop technique together with microstructural analysis were utilised to characterise radiant coils which were used at the naphtha cracker unit of petrochemical refinery industry. The tubes were non-magnetic in the virgin state and became magnetic after long duration of service. Magnetic hysteresis loop measurement indicated that the technique could be used for remaining life assessment of the radiant coil. A non-destructive test system developed at National Metallurgical Laboratory was also used for magnetisation measurement of the coils.

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