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ROOT CAUSE ANALYSIS ON FAILED SCREWS IN AN INDUSTRIAL TURBINE

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ABSTRACT

The failed screws of an industrial turbine hot section have been investigated. The broken screws were found during scheduled inspection of turbine with boroscope. Mechanical testing, optical microscopy (OM) and scanning electron microscopy (SEM) observation have been carried out on failed screws. The most crack positions were below the screws heads and cracks have propagated into the center. Analysis results identified unexpected Cadmium element on both fractured surfaces and screw body. Couple material (Ni superalloy-cadmium element), along with high temperature of combustor section and static load, resulted to liquid metal embrittlement (LME). As results of the present work, other similar failures were prohibited.

INTRODUCTION

The presence of select metallic species on the surface of various alloys can provide for very detrimental reactions under load known as solid-metal-induced embrittlement (SMIE) and liquid-metal embrittlement (LME). Sources of the aggressive elements vary; examples include unintentional or accidental exposure, unexpected interaction with material used for other reasons in the design, and misapplication (Cameron, 1994). LMIE, also known as liquid metal embrittlement, is the reduction of the fracture resistance and elongation of a solid material during exposure to a liquid metal (Augera et al, 2017; Augera et al, 2014). The important factors in this mechanism are presence of aggressive element, sensetive base metal, booster service condition and load as tensile stress. Cracking due to LME can be extremely rapid (m/s) and stress levels can be as low as 20 MPa for such cracking to take place (Heloise, 2004). Some failed screws from hot section of industrial turbines have been investigated and finally LME was identified as the main factor of failure.

METHODOLOGY

Several experiments such as spectroscopy analysis, hardness test, tension exam, microstructure analysis with electron and optical microscope have been carried out to find out the root cause of this fracture. The broken screws were made of Nickel base superalloy. Chemical analysis result (Table.1) of the broken bolt has been performed to ensure the conformity of material grade.

Table.1- Chemical analysis of broken screw

Element / condition	Si (max)	Mn (max)	Cr	Mo	Fe (max)	Ti	Al	Ni
Nominal (%wt.)	0.4	0.5	17.5-21	4-6	4	1-1.4	1.9-2.3	Base
Actual (%wt.)	0.27	0.01	19	4.8	0.64	1.2	2.1	0.08

Tension test has been carried out on in-service and new samples according to ASTM-E8, sub size samples. Tension test samples extracted from parts. Also, Brinell hardness (300 gr load) test has been performed on several new and broken screws. Allowable range of hardness is around 370 HB. The values of hardness for broken screws are higher than in-service parts due to age hardening of the screws in operational condition at service temperature. The test results of Table. 2 show that mechanical properties of screws are in accordance with requirements of manufacturing.

Table.1- Mechanical properties of in-service and new screws

	Sample Dia. (mm)	Area (mm^2)	Yield strength (MPa)	Ultimate strength (MPa)	El. %	Re %	Hardness (HB)
Nominal properties	-	-	686	1078	18	20	Max. 370
New samples	6.09	29.12	1069	1246	25.5	37	301*
In-service samples	6.09	29.12	895	1234	28	36	350*

*Note: value is average of minimum five hardness tests.

Fracture surface analysis

Fig.1a shows screw which was in service. *Fig.1b* shows head of broken screw that has been cut from middle in order to optical microscopy observation. The fracture surface of the failed screw and unbroken screws was covered by blue/yellow tints oxidized metals.

Fig.1- a) in-service screw, b) head of broken screw

Several intergranular cracks were observed at different zones. These cracks nucleated from outer surface and propagate inward (*Fig. 2*). The intergranular cracks accompanied metallic oxides are shown in *Fig.2b* by red arrows.

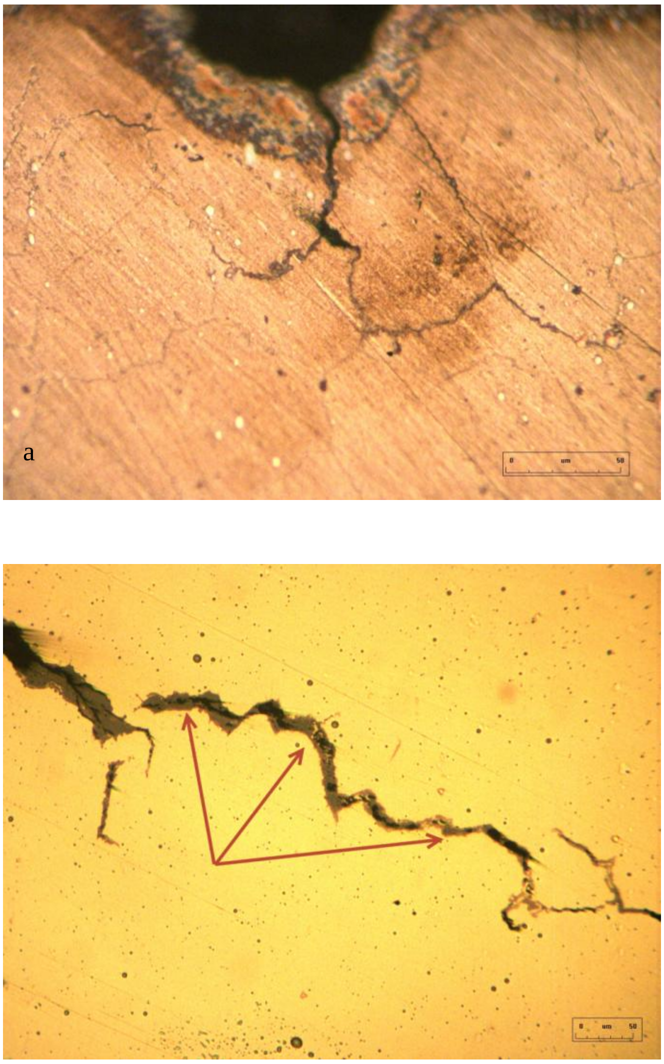
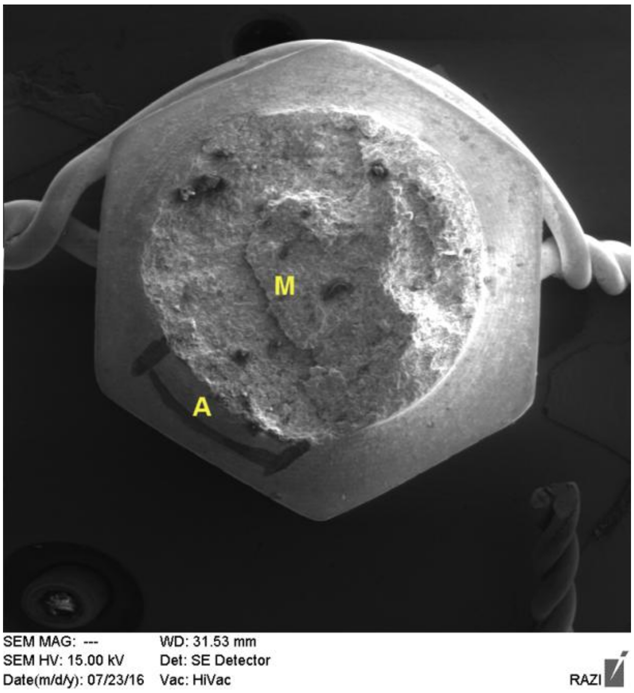
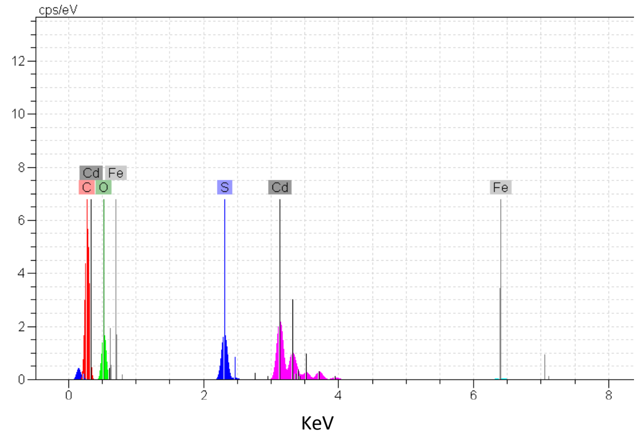


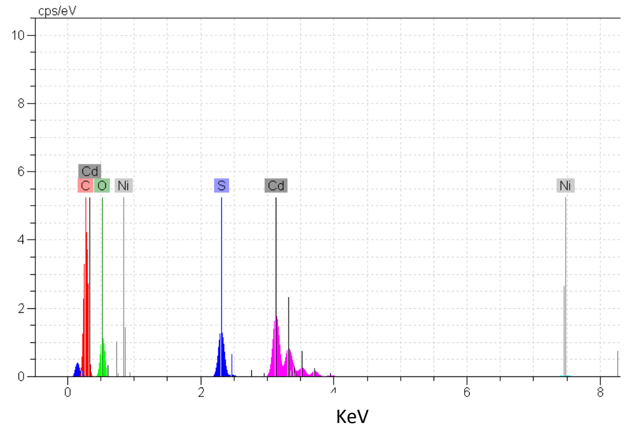
Fig.2- a) Intergranular crack has nucleated from outer surface, b) propagated crack with metallic oxide

Fracture surface has been analyzed with EDS (Energy-dispersive X-ray spectroscopy) method (*Fig. 3*). Some elements such as carbon, sulfur, oxygen, and cadmium were detected at points A and M. The source of sulfur, carbon and oxygen were reasonable but the presence of cadmium source is under question. The first two have come from anti-seize material and the last one from atmospheric air.





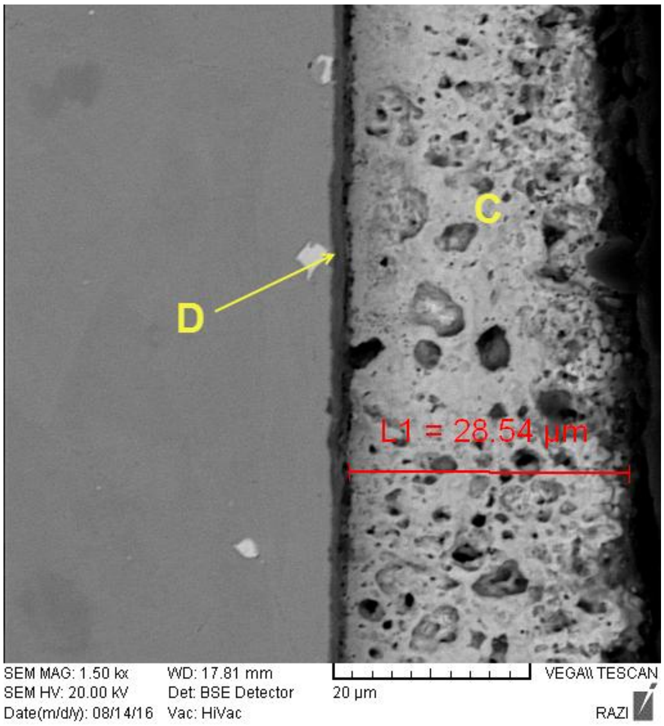
Spectra: A

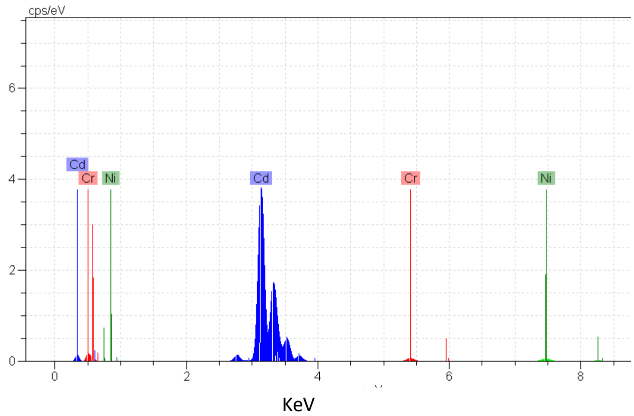


Spectra: M

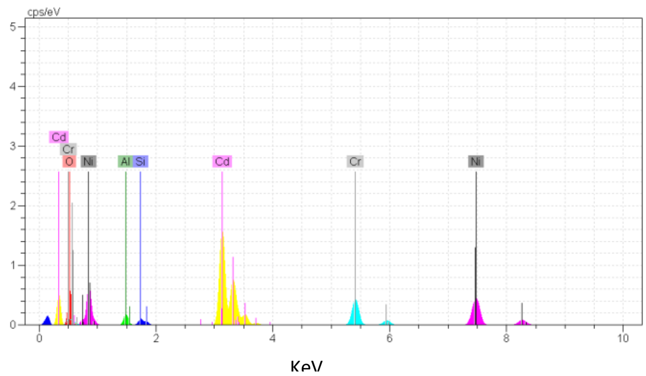
Fig.3- EDS analysis results of points A and M from broken surface

In order to examine more precisely, several other screws were evaluated. The results showed that all of the screws belonged to this machine were coated with Cadmium electroplating (*Fig.4*). It was identified that Observed colourful films (*fig.1a*) was cadmium oxidized.





Spectra: C



Spectra: D

Fig.4- EDS analysis results of points A and M from broken surface

Due to the fact that it was supposed to there is not any cadmium coating in the basic design, the investigations were continued to find the source of that. Finally, it became clear that the manufacturer was coated the screws coating bath.

RESULTS AND DISCUSSION

Presence of cadmium at Nickel based super alloys; high temperature service condition and stress can active Liquid Metal Embrittlement (LME) which can lead to fracture.

LME is a crack which nucleates as a consequence of liquid metal contact with a base metal. These cracks can quickly embrittle the material and contribute to fracture. Although, metal have a incubation time prior to embrittlement(Metals such as mild steels, low alloy steels, high strength steels, Austenitic stainless steels Seri, Nickel based super alloys, copper, aluminum, and titanium are susceptible to this phenomenon. This phenomenon occur when metals with low melting point such as zinc, mercury, lead, tin, cadmium and copper contact with susceptible metals while temperature is higher than their melting temperature(Lynch, 2008; Lynch, 2003). LME cracks can easily nucleate in interface between low melting point temperature and susceptible metals and propagate under tensile stress. Even a low amount of low melting point temperature metals can stimulate the LME phenomenon in susceptible metals. These cracks can nucleate after a long time of contact between melted metal and susceptible metals (Cameron, 1994). For components that are partially cracked by LME, and then cooled below the melting point of the embrittling metal, subsequent crack extension results in a localized ductile or brittle fracture through the embrittling metal, producing a dimpled or vein pattern on fracture surfaces when the embrittling metal is ductile (Lynch, 1992), *fig. 2* clearly shows these kinds of vein branchy cracks.

Screws have experienced approximately 500 ^{0}C in operation (*Fig. 5*). Since the melting point temperature of cadmium is 230 ^{0}C, working temperature lead to melting of cadmium. On the other hand, the hardness about 350 HB, high tension on nickel based super alloy screws and operation mechanical stress; provided a suitable condition for nucleation and propagation of LME cracks.

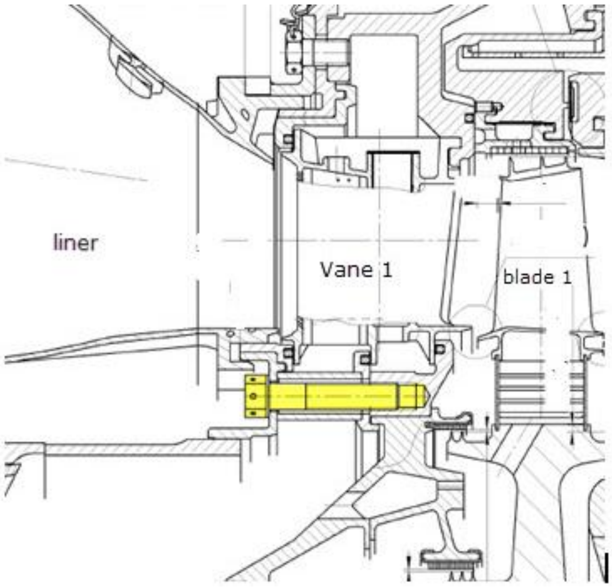


Fig.5- schematic of assembled screw in hot gas path system

LME occurs when contact with molten material of a lower-melting-point alloy results in a severe reduction in ductility and, very often, strength. This occurs primarily by intergranular entry of the molten metal into a stressed material, effecting progressive separation cracking or grain-boundary decohesion. Cycles of solidification and liquation of the low-melting-point alloy can also affect the extent and speed of this embrittlement, if volumetric expansion occurs during cycles of solidification or liquation. In Figure 6 and EDS analysis result, the presence of cadmium and its progression to the inside of the Intergranular crack is shown. It has been suggested that embrittlement is associated with liquid metal adsorption-induced localized reduction in the strength of the atomic bonds at the crack tip or at the surface of the solid metal at sites of stress concentrations. Adsorption-induced crack growth continues until the supply of liquid metal is ex-hausted, or the stress on the remaining section becomes high enough to produce such rapid overload cracking that capillary flow of liquid metal cannot keep up with the propagating crackThe full LME mechanism has been explained by other researchers (Heloise, 2004 Lynch, 2008; Lynch, 2003; Augera et al, 2014;).

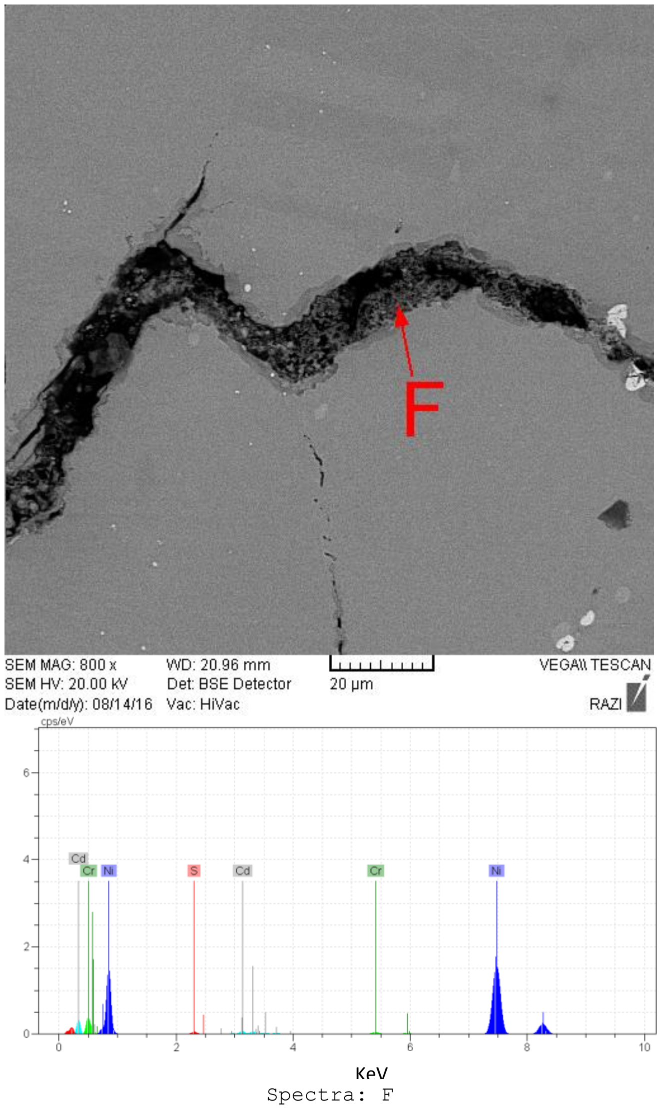


Fig.6-figure and EDS analysis of melted cadmium in intergranular crack is shown

CONCLUSION

The Screws failure which installed in hot gas path was due to Liquid Metal Embrittlement (LME). No metallurgical and mechanical deviations were found for the screw material with respect to the standard and related documents. It was due to a coating process which caused the entry of the cadmium element into pieces and proceeds to screw failure. Couple material Ni superalloy-cadmium element, innate high temperature of combustor section and static load have resulted in liquid metal embrittlement (LME). Nucleation and propagation of this crack led to failure. It was prevented by replacing them with new uncoated items.

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