FRACTOGRAPHIC AND MICROSTRUCTURAL INVESTIGATION OF THE FAILURE OF HIGH TEMPERATURE NIMONIC 80A INSERT BOLTS

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ABSTRACT

Nickel based superalloy Nimonic 80A is commonly used as high temperature bolting material in industrial power-generating units, due to its high creep rupture strength and adequate creep rupture ductility. In this research the failure of Nimonic 80A insert bolts, which connect the air duct rings to the combustion chamber ceiling, in a 159 MW unit is investigated. The bolts operating at about 650 ºC, failed prematurely after a service life of 36000 h. A broken fragment of the bolts dropped into the combustion chamber and entered the turbine section from a small design opening, severely damaging several of the turbine blades. Several insert bolts were retrieved from the accident site and used in this study. The investigation mainly included visual examinations, nondestructive testing, hardness testing, optical emission spectroscopy, metallography, and SEM fractography. The fracture location of the bolts was at the root of the first or second thread. Fractographic examinations identified intergranular creep rupture by wedge-shaped cracking as the operating failure mechanism. The macroscopically brittle fracture behavior of the insert bolts is discussed based on the formation of semi-continuous grain boundary carbide networks which resist grain boundary sliding, leading to stress build up and eventual loss of creep rupture ductility.

Keywords: Combustion chamber, Insert bolts, Intergranular creep rupture, Nimonic 80A.

1. INTRODUCTION

The present paper reports the investigation of the failure of Nimonic 80A insert bolts, which connect the air duct rings to the combustion chamber ceiling. The 159 MW capacity unit had a history of about 36000 h of safe operation prior to the accident. During normal service operation and without any prior indications a broken fragment of the bolts dropped into the combustion chamber and entered the turbine section from a small design opening, causing extensive damage to the turbine blades. The unit was then automatically shut down due to excessive vibrations. In preliminary examinations it was found that all three insert bolts of one of the rings in the combustion chamber ceiling were broken. In an attempt to retrieve the remaining insert bolts from other rings on the ceiling for further investigations, many of the insert bolts broke with the slightest applied torques during loosening.

The main scope of the activity of the failure analysis performed in this investigation was to identify the failure mechanism of the insert bolts and to clarify the role of material deficiencies with respect to the operative failure mechanism.

(a)

(b)

Figure 1. The combustion chamber rings (a) and a broken insert bolt (b).

2. EXPERIMENTAL METHODS

A total of 12 insert bolts including two remaining pieces of the main broken insert bolts, five insert bolts broken during loosening of the bolts, three insert bolts which did not brake during loosening and were retrieved without visible sign of cracking, and two new insert bolts were supplied for failure investigation. Chemical analysis was carried out using optical emission spectroscopy method. Nondestructive examinations of the three insert bolts which did not brake during loosening were carried out using liquid penetrant and radiographic inspection techniques. Specimen preparation for microstructural observations was carried out using standard metallography techniques, followed by etching the specimens with modified Kalling's reagent. Microstructural observations were conducted on sections parallel and perpendicular to the fracture surfaces of the insert bolts using optical and scanning electron microscopy. Macrohardness measurements were performed using Vickers hardness testing method at a load of 30 kgf. Following visual examinations, microfractographic studies of the fracture surfaces were conducted using scanning electron microscope. The specimens were subjected to ultrasonic cleaning prior to SEM examinations.

3. RESULTS AND DISCUSSION

3.1 Chemical analysis

Chemical analysis was conducted using optical emission spectroscopy method on specimen cut from the cross section of a broken insert bolt. The results of chemical analysis are shown in Table 1, which are in good agreement with the standard chemical composition for Nimonic 80A superalloy [1].

Nimonic 80A is a wrought nickel base superalloy which is particularly suitable for service under high stresses at temperature in the range 600 to 750 ºC [1-3]. Because of it's good stress relaxation resistance it is widely used for mechanical joining of high temperature parts [3,4], such as the insert bolts in the combustion chamber of the gas turbine unit, which operates at service temperatures lower than about 650 ºC.

Table 1. Chemical composition of insert bolts

Source of data	Composition (wt. %)				
Chemical analysis	C	Cr	Al	Ti	Ni
	0,031	20,3	1,3	2,6	balance
Nimonic 80A [1]	C	Cr	Al	Ti	Ni
	<0,05	19,5	1,4	2,4	balance

3.2 Nondestructive testing

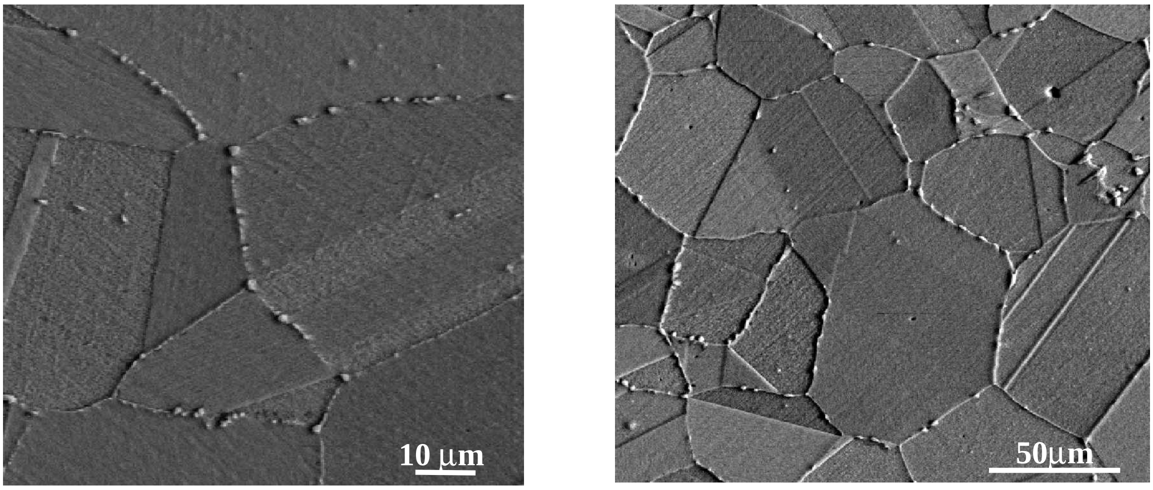
The unbroken insert bolts retrieved from the combustion chamber were subjected to nondestructive examinations using liquid penetrant and radiography methods. Cracks running around the roots of the first or second threads were detected by both methods. The cracking location was the same as that observed in the broken bolts, which is further discussed in section 3.5.

3.3 Hardness measurements

Macrohardness measurements (VHN, 30Kg) were carried along various sections of the insert bolts. The average hardness number of the bolts was found to be 360 VHN which is comparable to that of the new and unused bolts. However, at some locations the hardness numbers reached values as high as 430 VHN.

3.4 Microstructure

Representative SEM micrographs showing the microstructure of a new and unused bolt are shown in Figure 2(a,b). It can be seen that the microstructure mainly consists of equiaxed grains, twins, and a broad distribution of relatively coarse, distinct and globular grain boundary carbides, which are mainly the chromium rich Cr_7C_3 type carbide [1,3], as well as some carbides within the grains.

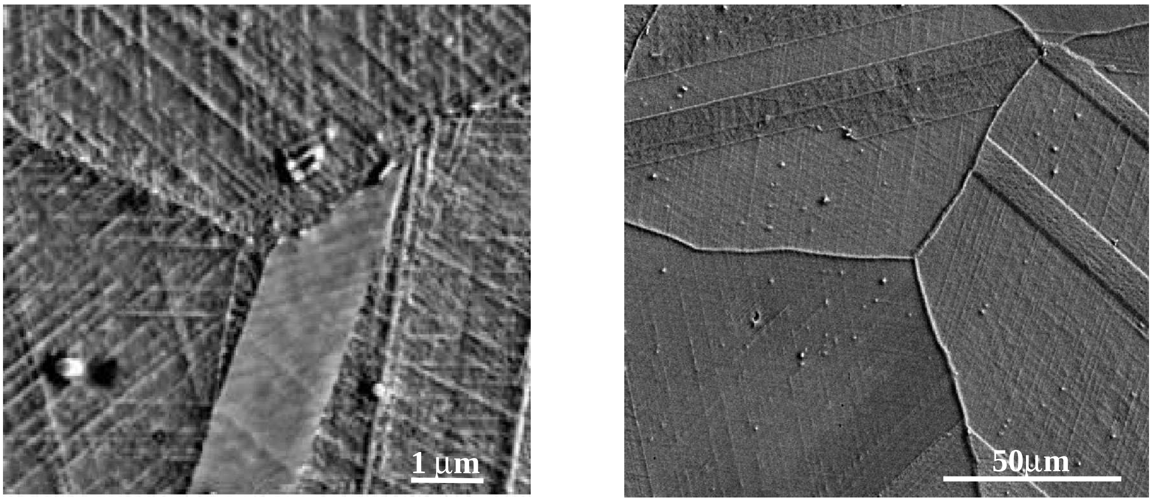


(a) (b)

Figure 2. SEM micrographs of a new insert bolt at low (a) and high magnifications (b).

The microstructures of broken insert bolts are also shown in Figure 3(a,b). Extensive precipitation of carbides on slip planes and formation of a more or less continuous grain boundary carbide layer are among the main microstructural features which can be identified in the broken bolts. The main carbides which precipitate during long time exposure at service temperatures of Nimonic 80A bolt material are $Cr_{23}C_6$ type carbides [1,3].

Furthermore, careful examinations of the microstructures of broken insert bolts in Figure 3(a,b) and other regions also reveal that distinct grain boundary carbides are not present. Distribution and morphology of grain boundary carbides is considered to have a pronounced effect on the mechanical properties and fracture behavior of Nimonic 80A superalloy [1,3-5]. A continuous film of carbides along grain boundaries provides a continuous fracture path and is therefore detrimental to the impact properties. Also it restricts grain boundary sliding during creep and leads to excessive stress concentration and early fracture [1,3-6].

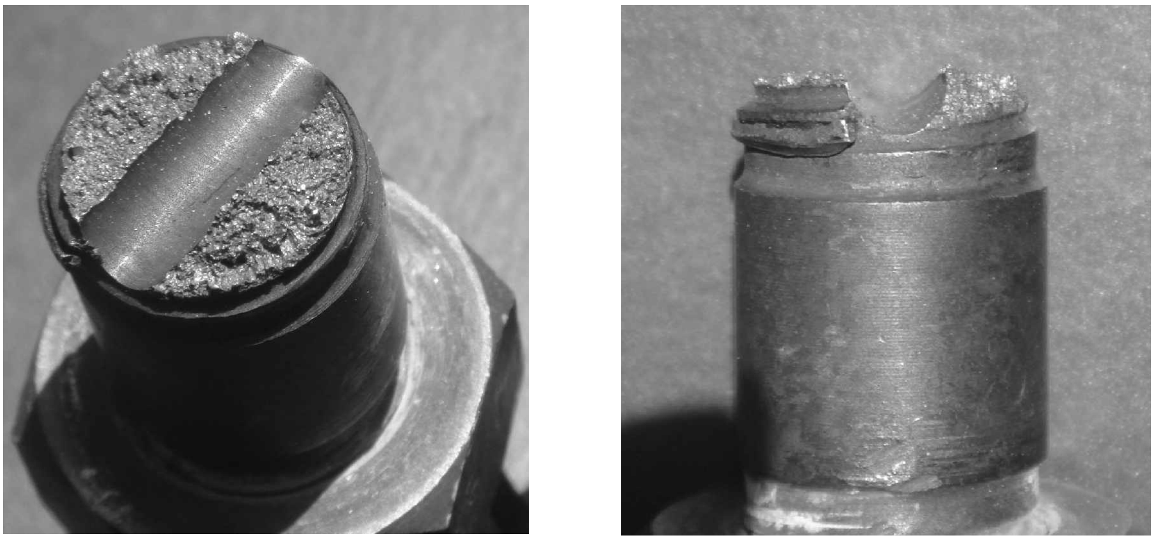


(a) (b)

Figure 3. SEM micrographs of broken insert bolts at low (a) and high magnifications (b).

3.5 Fractography

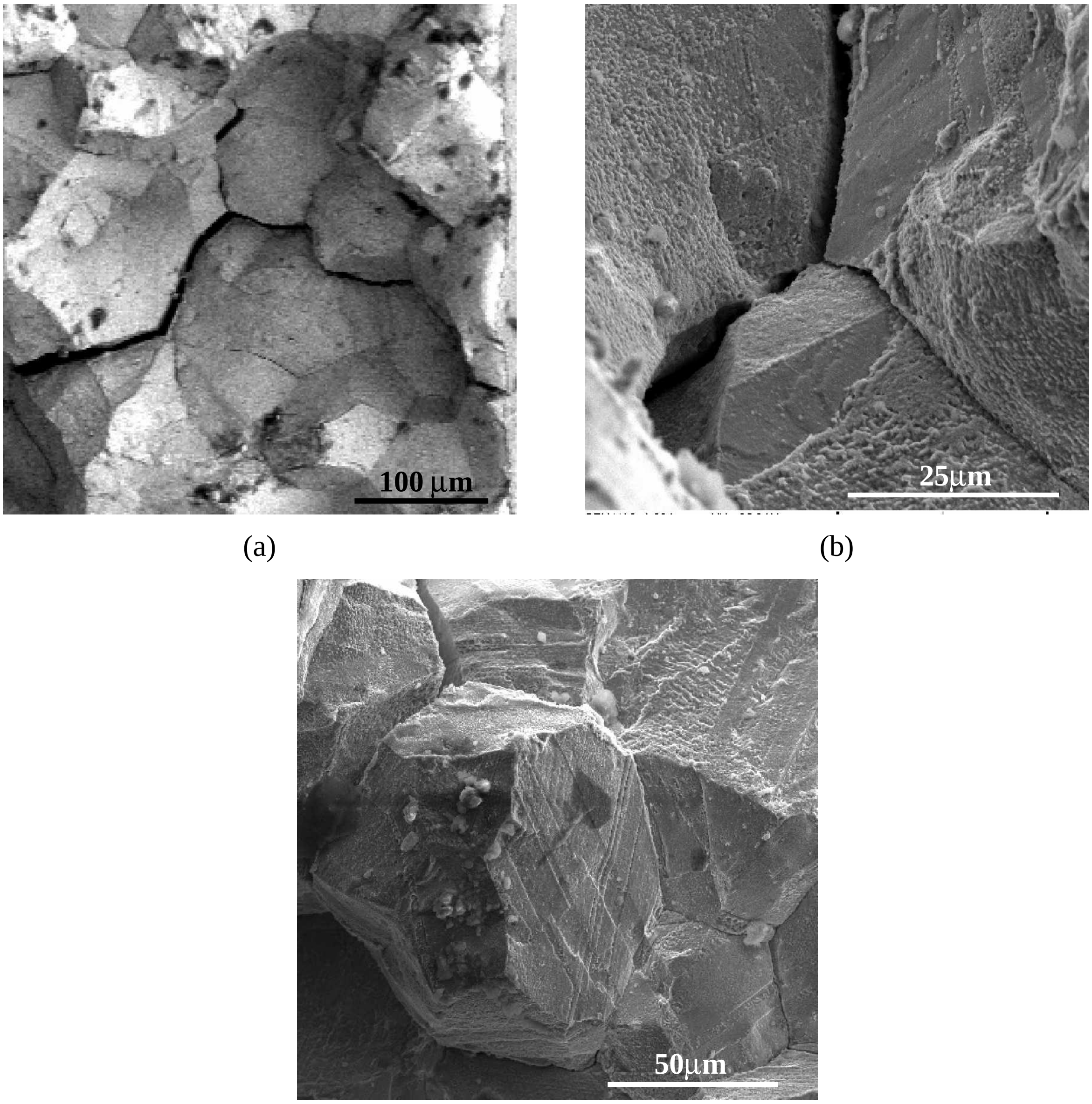
Figure 4(a,b) show the fracture surface of one of the main broken insert bolts. The fracture location of the bolts is at the roots of the first or second thread, which carry the highest loads [7]. The general orientation of the fracture surface is roughly perpendicular to the bolt axis. This fracture location and orientation coincides with that of other insert bolts which broke during loosening in preliminary inspections after the accident.



(a) (b)

Figure 4. Fracture surface of a failed bolt, (a) top view and (b) side view (2×).

A pin hole which is designed to keep the bolts tight and prevent it's loosening during service can be seen at the middle of the fracture surface crossing through the bolt. Macroscopic appearance of the fractured bolts indicates that the fracture process occurred without any measurable change in the cross sectional area or plastic deformation. Accordingly, the fracture process of the insert bolts can be categorized as a macroscopically brittle fracture process [8]. Furthermore, the fracture surface appears to be relatively rough. Fractographic observations using SEM revealed that this rough appearance is associated with cracking along grain boundaries rendering a three dimensional topography to the fracture surface as shown in Figure 5(a-c). Formations of wedge shaped cracks due to relative sliding of adjacent grains as well as widespread secondary intergranular cracking are among the main microfractographic features of the fracture surface.

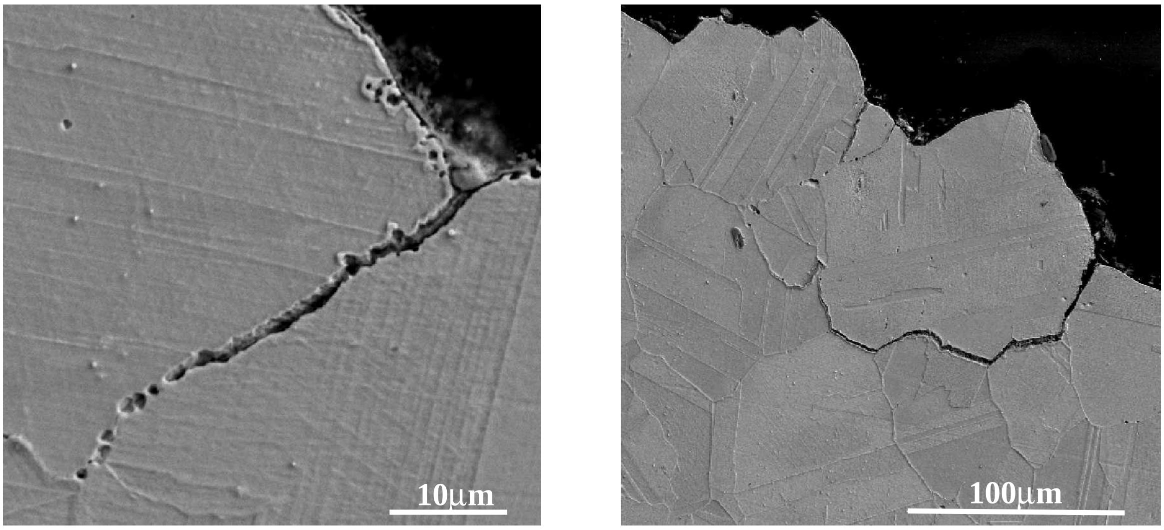


(a) (b)

(c)

Figure 5. SEM Fractographs showing (a) Intergranular fracture surface of a failed insert bolt, (b) Wedge type cracks, and (c) separation of a grain along most of its boundaries.

In order to further elucidate the relationship between the microstructure and fracture mechanism of the insert bolts, metallographic sections were cut at a 90 degree angle to the fracture surface and prepared for SEM observation. Significant advance of secondary cracks along the grain boundaries and a row of cavities extending downward from a triple point on the main fracture surface can be seen in Figure 6(a,b). In addition, close examination of the microstructure in this region also shows that particulate type grain boundary carbides are nonexistent or have a very limited distribution at best; instead a network of carbide layers is observed which delineates the grain boundaries in this region. The above findings show that intergranular creep fracture by wedge type cracking due to grain boundary sliding [6,8,9] was the main mechanism involved in the fracture of insert bolts.



(a) (b)

Figure 6. SEM micrographs showing (a) secondary crack advance beneath the fracture surface of a failed insert bolt and (b) a row of cavities extending downward from a triple point.

Extensive precipitation of carbides in the failed inserts bolts indicates that the alloy microstructure was unstable at the service temperatures lower than 650 ºC. This microstructural instability was promoted primarily by the lack of particulate grain boundary carbides which remain stable at the service temperature of insert bolts. Distribution and morphology of carbides along grain boundaries, which has a pronounced effect on creep rupture properties, is primarily controlled by the heat treatment procedure selected for Nimonic 80A bolt material [1,2,5]. The standard heat treatments of this superalloy include a two stage and a three stage process [1,2]. The two stage heat treatment consists of a high temperature solution at 1080 ºC followed by a low temperature aging at 700 ºC. This heat treatment has been shown to leave the matrix supersaturated in carbon, and thus on prolonged exposure to elevated temperatures, loss of ductility can result from further precipitation of carbides at the grain boundaries as well as within the grains [1,2]. The three stage heat treatment involves an additional intermediate temperature aging at 850 ºC to produce a distribution of coarse grain boundary carbides [1,2]. The distribution of distinct intergranular carbides in effect stabilizes the alloy microstructure and discourages or minimizes the precipitation of deleterious carbide layer networks at the grain boundaries [1,5]. This in turn increases the creep rupture strength at low stresses and high Larson-Miller time-temperature parameters [2]. Furthermore, creep-rupture ductility is also increased which is maintained during prolonged service at elevated temperatures [1,2]. The three stage heat treatment procedure is thus more suited to applications where long-term stability, together with the associated creep rupture ductility, are required such as in insert bolts [1,5].

Based on the fractographic and microstructural studied performed on the failed insert bolts in this research, the unexpected deterioration of creep rupture properties of the insert bolts can be attributed to the microstructural deficiencies resulting from an improperly selected heat treatment process selected for Nimonic 80A bolt material which did not provide a proper distribution of distinct grain boundary carbides. The resulting unstable microstructure encouraged precipitation of more or less continuous grain boundary carbide films during the service life of insert bolts leading to increased resistance against grain boundary sliding and stress build up at grain boundary triple points causing brittle intergranular creep fracture with minimal creep rupture ductility.

4. CONCLUSIONS

1- Macroscopically brittle intergranular creep fracture, by a wedge type cracking mechanism due to grain boundary sliding, was identified as the main failure mechanism of the combustion chamber insert bolts.

2- The fracture location of the insert bolts was at the roots of the first or second threads and the general orientation of the fracture surfaces was roughly normal to the bolt axis.

3- Extensive precipitation of carbides on slip planes and formation of a more or less continuous grain boundary carbide layer are among the main microstructural features in the broken bolts.

4- Precipitation of carbide layers at the grain boundaries during the service life of insert bolts which degraded the creep rupture properties, was attributed to the inherent instability of microstructures not properly heat treated to produce a distribution of coarse distinct grain boundary carbides in Nimonic 80A bolt material.

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