Journal of Achievements in Materials and Manufacturing Engineering

VOLUME 18
ISSUE 1-2
September–October
2006

Study of fracture mechanisms of a Ni-Base superalloy at different temperatures

S.A. Sajjadi*, S.M. Zebarjad
Department of Metallurgical and Materials Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, P.O. Box: 91775-1111, Vakil Abad Blvd., Mashhad, Iran
* Corresponding author: E-mail address: sajjadi@ferdowsi.um.ac.ir

Received 15.03.2006; accepted in revised form 30.04.2006

Properties

ABSTRACT

Purpose: The Ni-base superalloy GTD-111 gains its appropriate microstructure and high temperature strength through precipitation hardening mechanism. Because of their service condition, tensile properties of the alloy have strong influence on stability and life of the blades.

Design/methodology/approach: Tensile fracture mechanisms of the cast and heat treated superalloy were studied over a wide range of temperatures from 25 to 950°C with a constant strain rate of 10-4s-1. The present paper provides structural and fractography evidence by means of scanning electron microscopy at different temperatures for the superalloy GTD-111.

Findings: The variation in alloy ductility was found to correlate well with the fractography results of the tensile tested specimens. Transgranular and intergranular fracture with fine dimples, cleavage facets and a combination of them were shown in the fractographs.

Research limitations/implications: Although tensile properties alone are important for the alloy, it is suggested for future research to work on the simultaneous effects of tension and fatigue on the fracture mechanisms.

Originality/value: It was cleared that different fracture mechanisms operate in different temperature ranges; while transgranular dimple fracture was dominant at 650°C, the dominant fracture mechanism at room temperature was intergranular.

Keywords: Fracture mechanics; Ni-base superalloy GTD-111; Tensile test; Fractography

1. Introduction

GTD-111 is a Ni-base superalloy and has a multiphase structure consisting of γ matrix, γ' precipitate with a nominal composition of $Ni_3(Al,Ti)$, γ-γ' eutectic, carbides and a small amount of harmful phases such as: δ, η, σ and Laves [1-3]. The alloy obtains its high-temperature strength mainly through γ' precipitates which are present with more than 60% volume fraction. It is reported that the serrated grain boundaries increase creep life and creep plasticity through lengthening of the tertiary stage of creep and preventing grain-boundary sliding [4]. Sajjadi and Nategh [1], in an attempt to construct a deformation mechanism map for the alloy, have shown that different creep mechanisms operate in different creep conditions.

High-temperature strength of Ni-base superalloys depends mainly, on the volume fraction and morphology of γ' precipitates. Several basic factors contribute to the magnitude of hardening of the alloy [5].

The temperature dependence of tensile properties of many Ni-base superalloys have been studied [6-9]. Bettge et al.[8] studied the temperature dependence of yield strength of the Ni-base superalloy IN 738LC and concluded that, similar to other superalloys, the yield strength of IN 738LC decreases up to 450°C, then increases up to 750°C and finally decreases sharply. They attributed the variation to different deformation mechanisms operating at different temperatures.

Tensile deformation mechanisms of the Ni-base superalloy GTD-111 at different temperatures were studied recently [6]. The results showed that elongation increased with temperature reaching a maximum at about 650°C and then decreased to 7.7% at 750°C. Beyond that point an increase in elongation with respect to temperature occurred. At temperatures higher than 900°C, γ′ precipitate coarsening contributes to higher ductilities and lower strengths. The variations reported in the research are in good agreement with previous findings for IN 738LC by Bettge et al.[8] The results presented in the work [6] showed that different deformation mechanisms operate at different temperatures. Certainly, the effects of operating of these mechanisms affect the fracture behavior of the superalloy.

This work used tensile tests and scanning electron microscopy of specimens fractured at different temperatures to study tensile fracture mechanisms operating in each temperature range. It should be noticed that fractography is a powerful technique to determine fracture mechanisms of the fractured specimens.

2. Experimental procedure

Cylindrical specimens of 3.5±0.01mm in diameter and 19±0.1mm in gauge length were machined from 7mm diameter rods cut from a standard heat-treated blade made of Ni-base superalloy GTD-111. Table I gives the chemical composition of the material.

Table 1.
Chemical Composition of GTD-111 Superalloy (in wt.%)

Ni	Cr	Co	Ti	W	Al
Bal.	13.5	9.5	4.75	3.8	3.3
Ta	Mo	Fe	C	B	
2.7	1.53	0.23	0.09	0.01	

To prepare SEM fractography samples, fracture surfaces were cut from the gauge length of the specimens normal to the loading axis. They were cleaned and prepared using ultrasonic cleaner. Fracture surfaces were examined in LEO 1450 SEM to obtain information about failure mechanisms.

Tensile tests were carried out by using a Shimatzu tensile testing machine at a constant strain rate of $10^{-4}s^{-1}$ and according to ASTM E8 and E21 standards[10,11] at different temperatures from 25°C to 950°C. The temperature variation of the furnace during tension tests was about ±1°C. At least four specimens were tested at each temperature to obtain more precise results. Tensile properties such as: yield strength and elongation are included in Table 2,

3. Results and discussion

The fracture surfaces of the GTD-111 superalloy fractured in tensile tests at different temperatures were examined to correlate the fracture characteristics with structure and properties. Observation of fracture surfaces of specimens fractured at room temperature in tensile condition indicates a large number of grain boundary cracks with less than 200µm in length in the microstructure. There were not any evidence of voids on the fracture surfaces so, it was concluded that the cracks are due to the brittleness of grain boundaries and are not due to the void nucleation and growth. On the other hand, the study of the fractographs shows that the existence of precipitates in the grain boundaries is not the reason for the cracks but grain boundary carbides are responsible for crack formation. It should be mentioned that MC carbides precipitate frequently in the interior of grains but $M_{23}C_6$ carbides precipitate at grain boundaries. The separate grain boundary-carbides can improve mechanical properties and prevent grain boundary sliding[2]. Therefore, it is concluded this mechanism, is predominant at room temperature. Figure 1 shows the typical structures of specimens fractured at room temperature. The results are in accordance with the low elongation measured in the specimens.

Table 2.
Tensile properties of the Ni-base superalloy GTD-111 at different temperatures

Test Temperature (ºC)	Yield Strength (MPa)	Elongation (%)
25	850	3.7
550	730	5.1
600	710	7.2
650	740	13.1
700	780	9.8
750	830	7.7
800	685	12.2
850	550	12.9
900	460	13.4
950	375	13.7

At 550°C grain boundary cracks are seen in the microstructure. The difference between these specimens with the specimens fractured at room temperature is the observation of plastic deformation evidence in the specimens. Thus, it is clear that before fracture the specimens experienced a noticeable plastic deformation. The structure is shown in Fig. 2.

Figure 3(a) illustrates the structure of specimen fractured at 600°C. The structure consists of grain boundary voids produced during plastic deformation. The voids are coalesced and made grain boundary cracks. The dimples were about 10-20 µm in size. It is an evidence of void nucleation and growth during plastic deformation at high temperatures. Also, some transgranular fracture mode indicating of the brittle cleavage mechanism is observed (Fig. 3(b)). The presence of the two different fracture modes on the fracture surface simultaneously suggests a mixed mode of failure operating during tensile tests at 600°C that supports moderate ductility of the alloy.

With increasing temperature up to 650°C the effects of more plastic deformation can be seen clearly. The maximum ductility obtained at 650°C is attributed to the fine dimples present on the fracture surface indicating void coalescence and ductile intergranular fracture. As Fig. 4 indicates these effects are more extensive than Fig. 3(a). Therefore, it is expected to get more elongation than specimens deformed at lower temperatures. It is in accordance with what proposed by sajjadi et al.[6].

The structure of specimen fractured at 700°C shows transgranular cracks beside of intergranular ones formed during tensile test. The presence of the former restricts more elongation. The reason for the crack formation inside grains in these specimens is not exactly known.

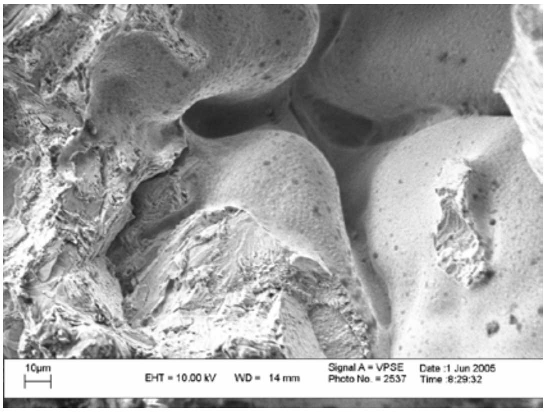


Fig. 1. Fractographs of a specimen fractured at 25°C at different magnifications

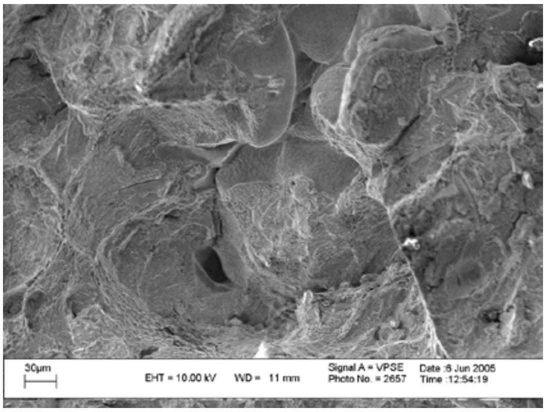
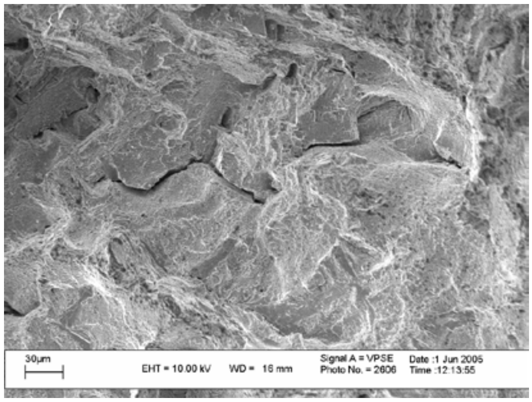


Fig. 2. Fractograph of a specimen fractured at 550°C

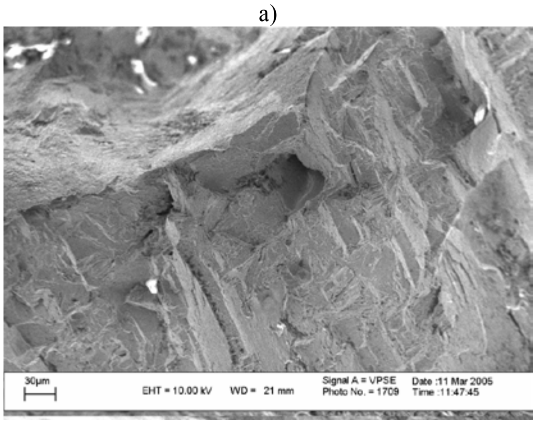
Grain boundary crack formation is the main reason for the minimum ductility produced at 750°C. The cracks were nucleated at the interface of the grain-boundary carbides and the matrix. Although, some voids were appeared around γ' precipitates in the microstructures obtained from interior of grains. In addition, cleavage evidence was observed in the specimens.

It was proposed[18] that three important factors can contribute to the minimum ductility of Ni-base superalloys. These are: i) Grain boundary embrittlement, ii) deformation mechanisms, and iii) γ' coarsening. Although, some investigators believe that cleavage fracture is the main reason for the low ductility of tensile specimens[9].

Cleavage fracture starts and propagates on the weak {100} planes of the fcc matrix. Such a fracture mode in the Ni-base superalloys was reported by several researchers[13-14]. Balikci et al.[9] studied fracture behavior of the Ni-base superalloy IN-738LC at different temperatures and postulated that cleavage crack propagation on {100} planes was probably aided by the fine γ' precipitates. According to many reports[13-15] when a growing crack intersects the γ' precipitate, it can propagate along the {100} planes of the precipitate since the cleavage planes are the same in the γ' precipitates and the matrix and also there is usually similar preferred orientation in the both phases.



a)



b)

Fig. 3. Fractograph of a specimen fractured at 600°C showing: (a): grain boundary cracks due to void coalescence; (b): transgranular fracture due to cleavage

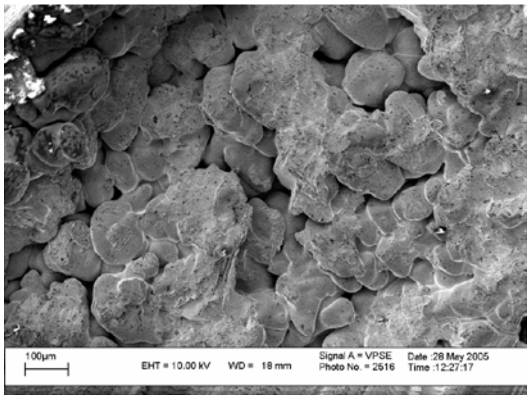


Fig. 4. Fractograph of a specimen fractured at 650°C; showing void nucleation and growth at grain boundaries

The presence of transgranular cracks is more noticeable in the specimens deformed at higher temperatures. With increasing temperature from 750°C, the voids grow fast and lead to the ductile fracture mechanism and higher elongation. The dimples are formed at the interface of carbides and matrix inside grains. The interfaces become weak at high temperatures and make transgranular cracks. In all specimens intergranular cracks can be seen but with increasing temperature the ratio of intergranular cracks to transgranular cracks decreases. Figure 5 shows the structure of fracture surface of specimens deformed at 850°C.

An interesting feature appeared in the fractographs is the effect of plastic deformation as fibrous zones on the fracture surfaces. The fibrous zones are produced by shear and propagate easily with increasing test temperature. So, more elongation is expected when temperature increases from 750°C to 950°C (Fig. 6).

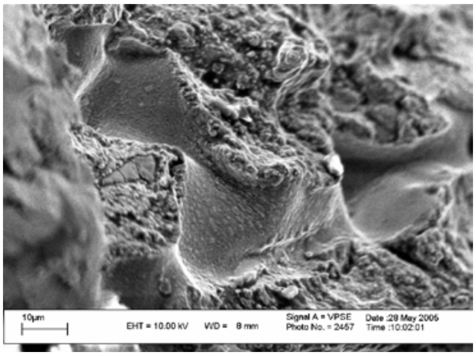


Fig. 5. Fractograph of a specimen fractured at 850°C

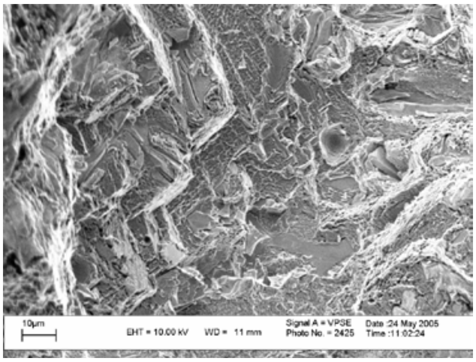


Fig. 6. Fractograph of a specimen fractured at 950°

4. Conclusions

The aim of this investigation was to study the fractography of the cast Ni-base GTD-111 deformed by tension at different temperatures. SEM investigation of the fractured tensile specimens indicated that the fracture mechanisms operating at each region are different. The occurrence of a given mechanism depends on the test temperature.

It was shown that the tensile fracture behavior was in agreement with the strength and ductility variation of the alloy with temperature. A fracture mechanism involving void formation occurs over a wide range of experimental conditions. Transgranular and intergranular fracture and cleavage are the other mechanisms operating in a specific temperature range.

Acknowledgements

The authors wish to express appreciation to Deputy of Research and Central Lab of Ferdowsi University of Masshad and Mavadkaran Eng. Co. for supporting of this project.

References

[1] S.A. Sajjadi and S. Nategh, A high temperature deformation mechanism map for the high performance Ni-base superalloy GTD-111, Materials Sci. and Eng. A, vol. 307 (2001) 158-164.
[2] S.A. Sajjadi, S. Nategh and R. I. L. Guthrie, Study of microstructure and mechanical properties of high performance Ni-base superalloy GTD-111, Materials Sci. and Eng. A, vol. 325 (2002) 484-489.
[3] S. Nategh and S. A. Sajjadi, Dislocation network formation during creep in Ni-base superalloy GTD-111, Materials Sci. and Eng. A, vol. 339 (2003) 103-108.
[4] Y. Zhang, Y. Wang, Z. Li, and C. Zhou, in: International Conf. on Strength of Metals and Alloys, (ICSMA 8), Pergamon Press, vol. 2, 1988, p. 941.
[5] S.A. Sajjadi, S.M. Zebarjad, R.I.L. Guthrie and M. Isac, Microstructure evolution of high-performance Ni-base superalloy GTD-111 with heat treatment parameters, J. Materials Processing Technology, in press, (2005).
[6] S. A. Sajjadi, S. Nategh, I. Isac and S M. Zebarjad, Tensile Deformation Mechanisms at Different Temperaturs in the Ni-Base superalloy GTD-111, J. Materials Processing Technology, 155-156 (2004) 1900-1904.
[7] [7] D. Siebörger, H. Knake and U. Glatzel, Temperature dependence of the elastic moduli of the nickel-base superalloy CMSX-4 and its isolated phases, Materials Sci. and Eng. A, vol. A298, (2001) 26-33.
[8] D. Bettge, W. Osterle and J. Ziebs, Temperature dependence of additional cyclic hardening of a nickel-base superalloy during out-of-phase multiaxial deformation, Scripta Metallurgica et Materialia, Volume 32, Issue 10, 15 (1995) 1601-1606
[9] E. Balikci, R. A. Mirshams and A. Raman, Materials Sci. and Eng. A vol. 265, Issues 1-2 , (1999) 50-62
[10] ASTM E8, Standard Test Methods for Tension Tests of Metallic Materials [Metric], 1998.
[11] ASTM E21, Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials, 1998.
[12] N.F. Fiore, Rev. High Temp. Mat., Vol. 2, (1975) 373-408.
[13] M. B. Henderson and J. W. Martin, Influence of precipitate morphology on the high temperature fatigue properties of SRR99, Acta Metall. Mater. 43 11 (1995), pp. 4035-4043.
[14] S.H. Ai, V. Lupinc and G. Onofrio, Influence of precipitate morphology on high temperature fatigue crack growth of a single crystal nickel base superalloy,Scr. Metall. Mater. 29 (1993), pp. 1385-1390.
[15] E. Balikci, R. A. Mirshams and A. Raman, Fracture behavior of superalloy IN738LC with various precipitate microstructures, MSE A, Vol. 265, 1-2, (1999) 50-62 .