FRACTURE AND FATIGUE BEHAVIOR OF ADDITIVELY MANUFACTURED MAR-M 509 CO-BASED SUPERALLOYS

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Abstract

Mar-M 509 is a Cobalt-based superalloy suitable for elevated temperature applications like nozzle guide vanes and blades in aero engines and gas turbines. Short cycle aging heat treatment of laser powder-bed-fusion processed Mar-M 509 is a novel route explored in this study to enhance the mechanical properties of this alloy, especially tensile ductility and fracture toughness, while retaining room and elevated temperature strengths. A detailed microstructural analysis is carried out using advanced characterisation tools and correlated to miniature, small volume, room temperature tensile tests and fracture toughness and fatigue tests using clamped beam geometry combined with digital image correlation-based in-situ strain mapping across the longitudinal and transverse directions, before and after heat treatment. Mechanisms leading to corresponding changes in fracture and fatigue properties will be discussed.

1. Introduction

Mar-M 509 is a cobalt-based superalloy exhibiting excellent oxidation and hot corrosion resistance designed to perform at elevated temperatures and find applications in static high-temperature components of aero engines and gas turbines like nozzle guide vane and turbines[1]. Mar-M 509 is strengthened by solid solution formers and carbides ($M_{23}C_7$ and MC) which precipitate around grain boundaries, and prevent grain boundary sliding at high temperatures [2]. Additive manufacturing of Mar-M 509 can produce end-use components with complex geometries while maintaining dimensional tolerance even while achieving rapid cooling. This eliminates the need for an additional solutionizing treatment. The application of cast Mar-M 509 is limited due to its low ductility(4%), but with additive manufacturing techniques, the superalloy exhibits enhanced mechanical properties [3]. Nevertheless the difference in microstructure in the build and scan planes results in a large degree of anisotropy in properties. In this study, the objective is to determine failure mechanism of Mar-M 509 produced using laser powder bed fusion (LPBF) additive manufacturing followed by short cycle heat treatments, under motononic and cyclic loads. The fracture and fatigue properties determined under various stress states using miniature, non-conventional test geometries are correlated with detailed microstructural analysis using advanced characterisation techniques. These novel small-volume test geometries minimize the sample size requirements and reduce material wastage.

2. Methodology and Results

The mechanical properties of additively manufactured Mar-M 509 were determined for as-printed and heat-treated samples in both orientations, i.e. longitudinal (L, loading direction along build direction) and transverse (T, loading direction perpendicular to build direction). In-situ strain measurements for these experiments were carried out using Digital Image Correlation (DIC). The as-printed samples were heat treated for 3 hours at 1250ºC in a vacuum furnace, followed by furnace cooling to room temperature. The microstructure characterisation was carried out using optical and electron microscopy. The tensile tests were carried out using a micro-tensile test, and plane stress fracture toughness was determined using miniature clamped beam bend geometry.

The microstructure consists of a weld bead structure with columnar grains elongated along the build direction in L and a raster scan pattern with the equiaxed grain on scan plane T (Fig 1). The carbides found along grain boundaries undergo both morphological as well as compositional changes post heat treatment, with the grain structure showing evidence of partial recrystallisation. The AM processed material exhibits near double the yield strength (1000MPa) and ultimate strength (1500MPa) with better ductility(11%) compared to the as-cast structure. The difference in strength along L and T is reduced after heat treatment.

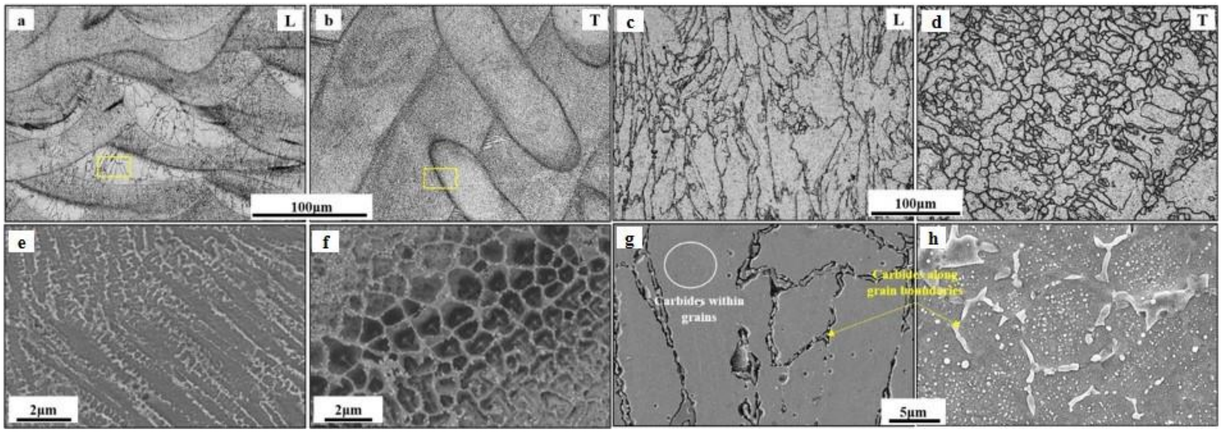

Fig.1 – Optical (a,b) and SEM (e,f) micrograph of as-printed samples and optical (c,d) and SEM (g,h) micrographs of heat treated samples along both orientation L and T of AM Mar-M 509

Based on the tensile properties, fatigue loading was carried out for both pre-cracking in fracture toughness tests (Fig 2) and for fatigue life assessment in low cycle conditions. K_{IC}, crack growth behavior and Paris law exponents were determined for both the AM and heat treated conditions at room temperature.

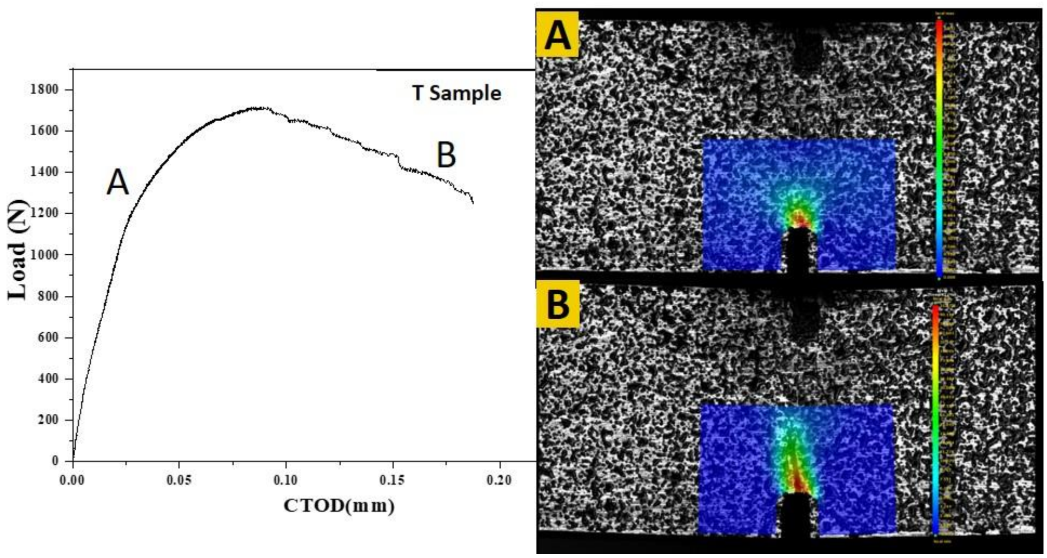

Fig.2 – Load vs CTOD curve obtained for clamped beam geometry where image A corresponds to crack initiation point followed by image B indicating crack propagation.

References

[1] Sh. Zangeneh and H. Farhangi, "Influence of service-induced microstructural changes on the failure of a cobalt-based superalloy first stage nozzle," *Materials & Design*, vol. 31, no. 7, pp. 3504–3511, Aug. 2010, doi: 10.1016/j.matdes.2010.02.021.

[2] D. Coutsouradis, A. Davin, and M. Lamberigts, "Cobalt-based superalloys for applications in gas turbines," *Materials Science and Engineering*, vol. 88, pp. 11–19, Apr. 1987, doi: 10.1016/0025-5416(87)90061-9.

[3] N. C. Ferreri *et al.*, "Effects of build orientation and heat treatment on the evolution of microstructure and mechanical properties of alloy Mar-M-509 fabricated via laser powder bed fusion," *International Journal of Plasticity*, vol. 121, pp. 116–133, Oct. 2019, doi: 10.1016/j.ijplas.2019.06.002.