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A study of the mechanism of laser welding defects in low thermal expansion superalloy GH909

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ABSTRACT

In this paper, we describe experimental laser welding of low-thermal-expansion superalloy GH909. The main welding defects of GH909 by laser in the weld are liquation cracks and porosities, including hydrogen and carbon monoxide porosity. The forming mechanism of laser welding defects was investigated. This investigation was conducted using an optical microscope, scanning electron microscope, energy diffraction spectrum, X-ray diffractometer and other methodologies. The results demonstrated that porosities appearing in the central weld were related to incomplete removal of oxide film on the surface of the welding samples. The porosities produced by these bubbles were formed as a result of residual hydrogen or oxygenium in the weld. These elements failed to escape from the weld since laser welding has both a rapid welding speed and cooling rate. The emerging crack in the heat affected zone is a liquation crack and extends along the grain boundary as a result of composition segregation. Laves–Ni_2Ti phase with low melting point is a harmful phase, and the stress causes grain boundaries to liquefy, migrate and even crack. Removing the oxides on the surface of the samples before welding and carefully controlling technological parameters can reduce welding defects and improve formation of the GH909 alloy weld.

1. Introduction

GH909 is an Fe–Ni–Co based, age-hardenable, low-thermal-expansion superalloy that is attractive for aerospace and land-based gas turbine engine applications [1–4]. GH909 alloy has been used in aircraft engine components to enhance the efficiency of jet engines through the control of clearances between turbine and/or compressor blade tips and outer seals and shrouds [5]. The main precipitation strengthening phase of this alloy is γ' ($Ni_3(TiA1)$), which is a face-centered cubic lattice. Since this alloy contains 0.4% silicon, it is resistant to stress-accelerated, grain-boundary oxidation (SAGBO) brittleness at high temperature. This alloy has a high strength, low expansion coefficient and almost constant modulus of elasticity under 650 °C, which can improve the efficiency of the engine and reduce the fuel and oil consumption by lessening the gap between engine blade and sealing ring of accessory gearbox.

Welding is necessary to achieve the joining of GH909 alloys. GH909 has good weldability, so it can be welded using argon arc welding (TIG) [6], inertia welding [7] etc. Compared with traditional TIG welding however, laser welding produces a narrower heat-affected zone, since lower energy input is applied per unit length, reducing thermal distortions [8]. The laser welding process is always automated, minimizing the frequency of required rework [9].

There are certain tendencies that lead to liquation cracking in the weld and microcracks in the heat affected zone when welding this alloy. Considerable research on welding defects such as cracks and porosities is currently under way. Shankar et al. [10] demonstrated that hot cracking in stainless steel welds was caused by low-melting eutectics containing impurities such as S, P and alloy elements such as Ti and Nb. Segregation was found to play a significant role in cracking susceptibility. Ebrahimzadeh et al. [11] found that the formation of hot cracks in

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the weld metal depended on the weld pool shape. Cylindrical weld pools were sensitive to hot cracks. Hayes [12] thought that grain-boundary (GB) cracking was due to the penetration of oxygen along grain boundaries and subsequent oxidation of GB particles, i.e., carbides and possibly delta phase present at the boundaries. Huang et al. [13] confirmed that porosity formation was associated with the evolution of gas, especially hydrogen. Zhao et al. [14] determined that porosity was induced by keyhole due to its depth self-fluctuating during continuous laser welding, and the bubbles formed as a result of keyhole collapse and shrinkage. Porosity formation was chiefly attributed to the gases in the pre-existing pores in the base material swelling to form bubbles during welding. These bubbles had few opportunities to escape from the weld molten pool because of the vigorous melt flow and the rapid solidification associated with high welding speeds [15].

However, oxidation resistance is very poor, because GH909 alloy has little Cr. Thus it is quite difficult to achieve an acceptable weld without imperfections while retaining acceptable mechanical properties using laser welding. Hot cracking of GH909 alloy will not only limit the scope of application for the new material, but also induce reheating and fatigue cracks [16], leading to terminating production of certain products and may even compromise airplane safety [6].

The purpose of this research is to study the forming mechanism of laser welding defects in low thermal expansion superalloy GH909 and explore methodologies to reduce the porosity and cracking in the weld during laser welding in order to obtain a joint with good performance. This research project will also evaluate the feasibility of laser welding GH909 alloy as a means to improve the efficiency of aircraft engine production.

2. Experimental Procedure

The aim of this study was to determine the cause of porosity and cracking and devise a method or methods to eliminate defects and attain an acceptable weld without imperfections.

The experimental laser is an Ytterbium Fiber laser, YLR-4000. The experimental materials are GH909 alloy, the chemical compositions of which are described in Table 1. Samples were all the same dimension: 56 mm × 32 mm × 2 mm. Before laser welding, the oxidation film and greasy dirt on the surface of substrates were eliminated by a series of mechanical and chemical cleaning methods.

Welding with a high-power fiber laser (HPFL) was performed on GH909 alloy using three variables: laser power, welding speed and focal point position. Process variables of continuous laser welding are described in Table 2. The laser welding head was mounted on an industrial robot (ABB), which pushed the laser welding head over the clamped sheets at the desired welding speed. Before each test, acetone was used to clean the edges of the test pieces. The samples were firmly fixed flat on the jig so that the welding optics were inclined to the direction of the welding and the work piece surface to prevent splash metal from damaging the lens during the laser welding. Argon, with a flow rate of 41.7 l/min was used as a shielding gas, delivered to the weld via a copper tube. The schematic of the laser welding setup is listed as Fig. 1.

Table 2 – Process variables of continuous laser welding.

Equipment	Variables	Units	Levels
YLR-4000	Laser power	kW	3.6, 3.8, 4.0
	Welding speed	m/min	4, 5, 6, 7
	Focal point position	mm	0
	Shielding gas, flow	l/min	41.7

The preliminary experiments revealed that the focal point position of 0 mm was proper for welding GH909 with a 2 mm thickness. After welding, the samples were cut from the laser welding joint using a line cut machine. All samples were shaped using different types of sand paper, then polished and etched with solutions including 25% HNO_3 mixed with hydrochloric acid. Metallographic examinations were first conducted to examine the microstructure features near the GH909 alloy interface. Morphology analysis was conducted using a scanning electron microscope (SEM). The element distribution and phase constitution of the GH909 alloy laser welding joint were then analyzed by means of energy diffraction spectrum (EDS) probe combined with SEM and X-ray diffractometer (XRD) respectively.

3. Results and Discussion

3.1. *The Defects of Welded Joints*

The microstructure near the interface of GH909 alloy' laser welding joint can be observed through an optical metallographic microscope in Fig. 2. We see that the base metal contains mainly the primary γ phase (large blocky structure), γ' phase (granules or smaller pellets in the interior of the grains) and a small number of Laves phase (short rods in the grain boundary) in Fig. 2a. Some researchers [17,18] found that blocky A_2B Laves phase was abundant, which can prevent excessive grain growth up to approximately 1040 °C. The major defects in the weld were found to be cracks and porosity. The serration crack appeared in the heat affected zone (HAZ), spreading along the direction of the grain boundary from the weld to the base metal (Fig. 2b). Grain boundary cracks were generally associated with high-energy, high angle grain boundaries [19].

Compared with base metal, γ' phases in the HAZ decreased and the microstructure of the HAZ exhibited an increased coarseness. The ε phase grew rapidly with the dissolution of

Table 1 – GH909 alloy chemical compositions & ranges.

Materials	Chemical compositions (wt.%)							
	C	Ni	Co	Ti	Al	Si	Nb	Fe
GH909	≤0.06	35–40	12–16	1.3–1.8	≤0.15	0.25–0.5	4.3–5.2	Bal