Materials Science and Engineering A 421 (2006) 168–181

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Creep and tensile behaviors of Fe–Cr–Al foils and laser microwelds at high temperature

Haitham El Kadiri [a,*], Yves Bienvenu [b], Kiran Solanki [a], Mark F. Horstemeyer [a], Paul T. Wang [a]

[a] *Center for Advanced Vehicular Systems, Mississippi State University, MS 39762-9627, USA*
[b] *Ecole des Mines de Paris, Centre des Matériaux, CNRS UMR 7633, BP 87, 91003 Evry, France*

Received 20 April 2005; received in revised form 1 November 2005; accepted 21 November 2005

Abstract

We examine a Fe–Cr–Al foil-based material and a continuous-wave laser weld generated in ultra-fine "keyhole" mode undergoing tensile and creep-tension tests over a temperature range of 25–1000 °C. At all temperatures, the bead exhibits superior tensile resistance than the base material due to a homogenous reprecipitation of fine aluminum nitrides, AlN, but creeps faster at 900 °C, because of a finer-grained microstructure scarcely undergoing secondary recrystallization. Under tensile loading, the base material ductility is higher than that of the weld and increases with increasing temperature, but drops above 900 °C due to faster grain growth and chromium carbide precipitation. The base material stress–strain curves exhibit concomitant decrease of the yield point effect magnitude and increase of the strain hardening rate with the temperature, but only up to a critical value, which decreases with increasing the strain rate. After vanishing at this critical temperature, the yield point effect reappears upon the onset of sample necking responsible for the ensuing continuous decrease of the engineering stress. The strain–stress curves of laser welds show no yield point effect and the work hardening persists at all temperatures. Under creep-tension, the weld shows a strong anisotropic behavior, and the highest flow rate is recorded for welds oriented parallel to the loading direction, because of a more important cavity nucleation.

Keywords: Catalytic converter; Fe–Cr–Al foil; Laser welding; Finite element simulations; High temperature; Creep; Tensile; SEM; TEM

1. Introduction

Although Fe–Cr–Al-foil substrates are associated with a less cost-effective catalytic converter monolith design than extruded ceramics, they offer decisive technical advantages: less thermal inertia, shorter light off time, less risk of overheating, lower back-pressure, superior performance at elevated temperatures, easier recycling and possibility to manufacture large size components for heavy duty applications [1]. These properties allow the metallic converter to be electrically preheated and positioned closer to the engine, thereby increasing the conversion rate for closer compliance with the Zero Emission Vehicle (ZEV) standards becoming effective in 2005 [2]. However, these measures lead to a more severe thermal loading of the material and structure at the risk of not producing high quality and affordable systems required by the fast-growing market and global competition [3]. These engineering challenges drive the need for advanced design control at two key-manufacturing phases:

- The shaping process of the monolith base material, a ferritic refractory stainless steel, usually Fe–Cr–Al with 20 wt.% Cr and 5 wt.% Al with a foil thickness coming down from 200 to 25 μm;
- The joining process used to make the spiraled monolith into a "rigid" structure using for metallurgical fixture for a casing tube, also a refractory stainless steel. These aspects will be treated in a different paper.

In addition to a shorter total Al depletion, reducing the foil thickness results in a more pronounced creep-buckling of the foil under the compressive growth stresses associated with the inward growth mechanism of the oxide, which predominates in the range of very high temperature (≥1100 °C). The foil buckling, on one hand, decreases the conversion efficiency of the catalyst by sagging the honeycomb cells, and on the other hand promotes scale spallation that results in a faster onset of the breakaway oxidation. Even in the range of low temperature

---

[*] Corresponding author. Tel.: +1 662 325 5568; fax: +1 662 325 5433.
E-mail address: elkadiri@cava.msstate.edu (H. El Kadiri).

0921-5093/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.msea.2005.11.048

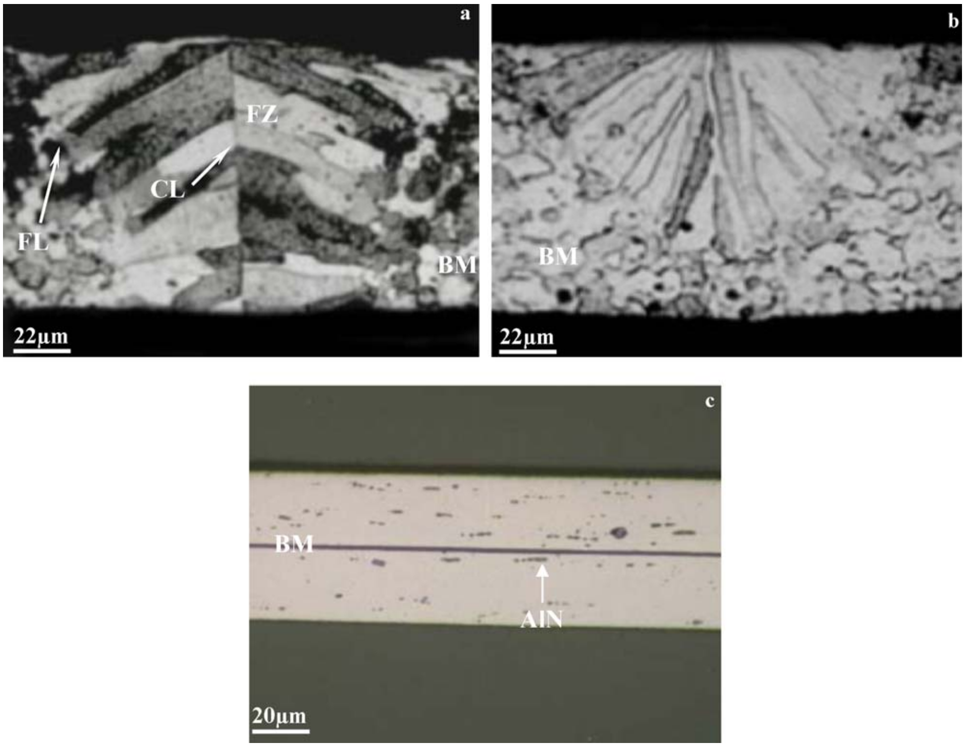

Fig. 1. Optical micrographs of etched cross-section microstructures laser beads and BM: (a) full penetration with $P = 400$ W and $V = 37$ m/min, (b) partial penetration with $P = 400$ W and $V = 46$ m/min, and (c) polished cross-section of two foils down to 1/4 μm, displaying alignment trains of AlN.

(<1100 °C), where the substrate undergoes much lower creep, the systematic tensile growth stresses induce dramatic interfacial cavities that grow independently of the substrate Al-reservoir. A reduction of the foil thickness will consequently lead to more severe damage progression and earlier failure of the component. Besides these effects on the behavior and fracture toughness of the foil, growth stresses in the foil directly affect the oxidation kinetics, and the diffusion fluxes are driven by both composition and heterogeneous stress gradients. Moreover, the relaxation rate of growth stresses by creep influences the oxidation kinetics since creep facilitates the phase transformation rates of the fast-growing metastable aluminas by promoting interface recession [4]. Fundamental understanding of the mechanical properties of Fe–Cr–Al foils is therefore critical for developing new affordable alumina-forming iron-based alloys, allowing thinner foils to be manufactured and used with adequate formability and lifetime expectations [5–7]. The main scope of this paper is to study the mechanical properties of the Fe–Cr–Al foil and a laser beam weld in an effort to validate an autogenous laser beam welding for assembling the honeycomb-style catalyst during the coiling of the monolith in the "flying optics" principle [8–11]. We examine and compare the mechanical properties of the base material (BM) and an optimized laser beam condition-generated microstructure through tensile tests over a temperature range of 25–1000 °C and creep-tension tests at 900 °C over a stress range of 1–40 MPa. The results are elucidated from microscopical observations and analyses using optical microscope (OM), scanning electron microscope (SEM), transmission electron microscope (TEM), and electron probe microanalysis (EPMA) techniques.

2. Laser welding experiments

A 400 W FEHA SM 400P CO_2 gas transport laser delivering a very narrow beam with a maximum diameter of 70 μm for a 30 mm focal length was used to weld two foils of 45 μm without noticeable morphological defects. Bead-on-plate welding tests were performed on a 95 μm thick Fe–Cr–Al foil. This laser offers a moving lens up to 100 m/min and delivers a beam with Gaussian-distribution energy.

The best welding condition corresponds to a peak power of 400 W and a welding speed of 37 m/min. This condition generates a fusion zone (FZ) 100 μm large at the upper face and 70 μm wide at the bottom side (Fig. 1a and b). All the weld lines were achieved at the focal point and a 10 l/min argon shielding gas was used to limit oxidation, with a nozzle located at the rear part of the melting pool. A four-point clamping tool with a 2 mm-large full-penetrated window was used to minimize the focal distance variation along the welding track. Prior to welding, the samples were ultrasonically cleaned in acetone and dried.

3. Base material and laser weld microstructures

3.1. Crude microstructures

3.1.1. Base material

The Fe–Cr–Al alloy is a Sandvik 0C404 type with a low interstitial (C + N) level, "co-doped" with mishmetal (Ce + La), cold rolled down to 45 and 95 μm and annealed. Quantitative analysis of major and trace elements with Energy and Wavelength Dispersive X-ray analyses (EDS and WDS, respectively)