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Microstructure and tensile properties of laser engineered net shaped reduced activation ferritic/martensitic steel

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ABSTRACT

A laser additive manufacturing technique, laser engineered net shaping (LENS), was successfully applied to manufacture a reduced activation ferritic/martensitic (RAFM) steel with nominal composition of Fe-9Cr-0.11C-1.5W-0.4Mn-0.2V-0.12Ta (wt%). The as-deposited LENS-RAFM steels were normalized and tempered. The microstructures of as-deposited and heat treated LENS-RAFM steels were characterized by using optical microscope (OM), scanning electron microscope (SEM) and transmission electron microscope (TEM). The tensile tests of as-deposited and heat treated samples in different directions were carried out at room temperature and 873 K. The results showed that columnar dendrites grow epitaxially along the direction of deposition in vertical section (YOZ) and a mixture of equiaxed and columnar grains appears in horizontal section (XOY). No precipitates are observed in the as-deposited sample while Cr-rich $M_{23}C_6$ and Ta-rich MX type carbides appear in the heat treated sample. The as-deposited sample showed anisotropic tensile properties which could be eliminated by heat treatment. The tensile strength of the LENS-RAFM steel is similar to conventional RAFM steels such as EUROFER 97 and CLAM.

1. Introduction

Several tritium breeder blanket concepts have been developed for Test Blanket Modules (TBMs) in International Thermonuclear Experimental Reactor (ITER), including helium-cooled lithium-lead (HCLL) and helium-cooled pebble-bed (HCPB) in Europe, water cooled ceramic breeder(WCCB)in Japan, dual-coolant lead-lithium (DCLL) in US, helium-cooled ceramic breeder (HCCB) and dual functional lithium-lead (DFLL) in China [1]. Reduced activation ferritic/martensitic (RAFM) steels have been chosen as structural materials to fabricate these TBMs owing to their low irradiation swelling and thermal expansion coefficient, high thermal conductivity and good mechanical properties [2–4]. The complicated structure and shape of RAFM steel subcomponent require advanced joining technologies, e.g. hot isostatic pressing and diffusion welding [5,6]. The complexity of this process results in high costs and long manufacturing time.

The rapid development of additive manufacturing techniques provides a potential method for fabrication of RAFM steel subcomponents. Laser engineered net shaping (LENS) is one of the additive manufacturing techniques by which components can be built up layer-by-layer by melting and depositing powder into a net-shape. Compared with conventional manufacturing processes, LENS has unique advantages, for example, high materials utilization, short manufacturing cycle, low manufacturing cost and great flexibility. LENS technology has been applied to fabricate Ni-base [7,8], Ti-base [9,10] and Fe-base [11,12] materials. Recently Ordas fabricated TBM geometrically relevant components with P91, which is a ferritic/martensitic commercial steel but does not satisfy the reduced activation requirement in ITER, by selective laser melting and hot isostatic pressing (HIP). The P91 specification was obtained by appropriate heat treatment and high precise dimensional control was achieved [13]. The CLF-1 (one of the RAFM steels) was produced by Laser Solid Forming (LSF) which is similar with the LENS process and the room-temperature tensile properties of the LSFed CLF-1were analyzed [14]. However, the microstructure and elevated temperature tensile properties for LSFed CLF-1 were not reported.

The standard heat treatment of conventional RAFM steels consists of normalizing and tempering before application. S. Chen et al. [15] and Q. Wu et al. [16] researched the effect of heat treatment on laser welded and electron beam welded RAFM steels, respectively. It is

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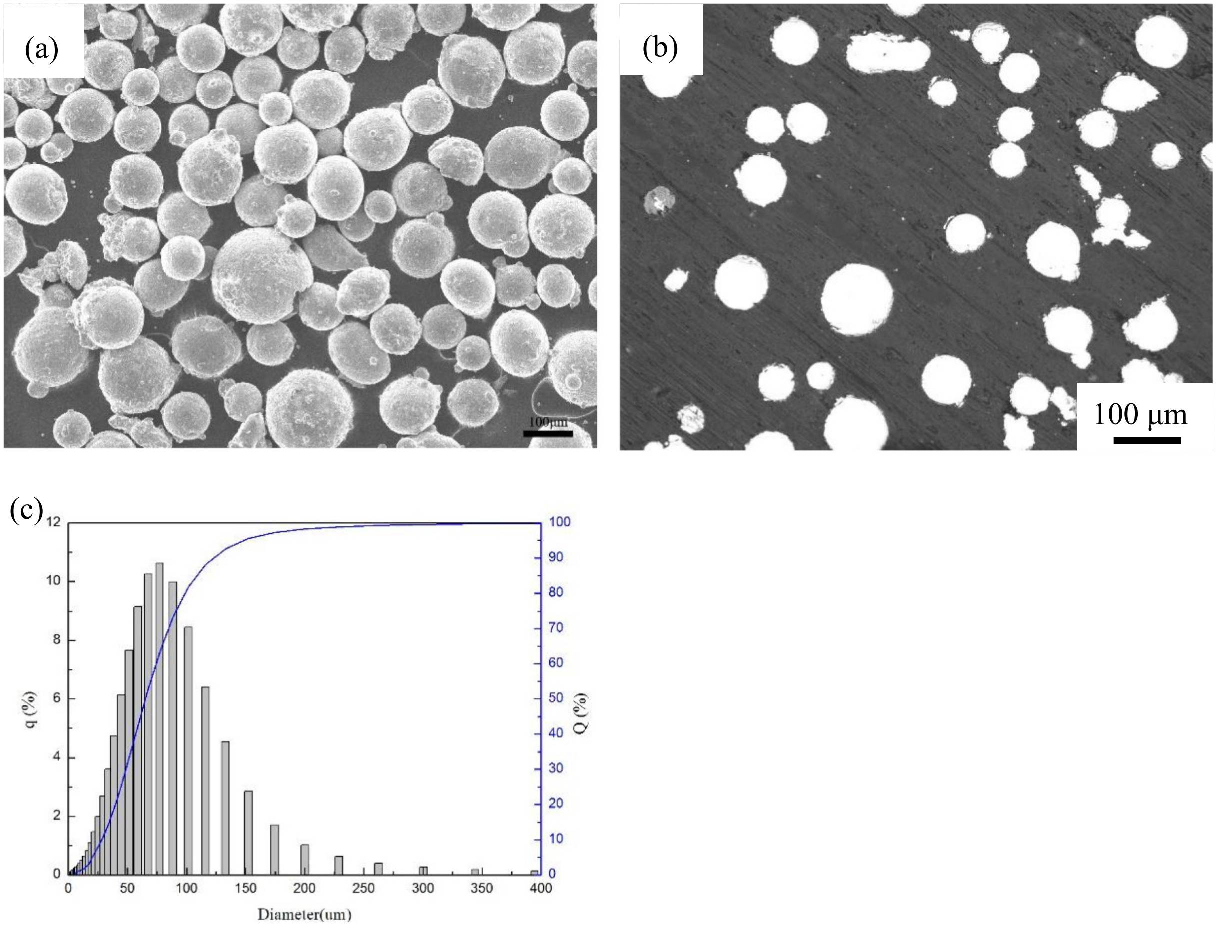

Fig.1. (a) SEM image of atomized RAFM powder, (b) metallographic image of cross-section of powders, and (c) particle size distribution.

suggested that post-weld heat treatment is an effective way of improving the mechanical properties of the joint. However, there are no published literatures about the effect of heat treatment on microstructure and mechanical properties at different temperatures of laser additive manufactured RAFM steels. In this study, we utilized RAFM prealloy powder produced by gas atomization as raw material and fabricated fully-dense bulk RAFM steel using LENS process. The microstructures of the as-deposited RAFM steel before and after heat treatment were examined carefully. The room and elevated temperature tensile properties of both as-deposited and heat treated RAFM steel were also explored.

2. Experimental

The RAFM steel powder with average particle size of 72.8 µm was manufactured by gas atomization. The morphology and particle size distribution of atomized powder are presented in Fig.1. The powders exhibit spherical shape and the metallographic sections reveal that no obvious hollow powder particles are observed. The chemical composition is listed in Table 1. The gas atomized powders were sieved and the powders with size of 50–150 µm were employed in this study.

The bulk RAFM steels were manufactured using LENS machine which was a self-assembly apparatus in Shenyang Aerospace University. The equipment is mainly composed of IPG fiber laser, numerical control system, coaxial powder feeder, inert gas dynamic protection system and infrared temperature measurement system. Scanning strategy was zigzag scan vectors. Before the experiment, the building chamber was filled with argon gas. The content of O_2 and H_2O was below 80 ppm and 30 ppm in the working chamber. The substrate was AISI 1045 steel. To achieve dense and crack-free samples, the process parameters used in this study are listed in Table 2. In this study, the feed rate is the laser head movements. The schematic of deposition is presented in Fig.2. The direction of deposition is along the Z direction, and X direction is the scanning direction.

The LENS manufacturing process starts with a solid CAD mode that is sliced in the next step by the sliced software (independent programming by Shenyang Aerospace University). Sliced layer thickness is 0.5 mm and hatch distance is 1.8 mm. Based on the prepared slice file, the scanning path is generated and deposition is carried out.

The as-deposited sample was separated from the substrate with wire-electrode cutting. The as-deposited samples were normalized at 1253 K for 30 min followed by air cooling, then tempered at 1033 K for 90 min and air cooled.

The density of the as-deposited sample was tested by Archimedes

Table 1
Chemical composition of RAFM steel powder.

Element	Fe	C	Cr	W	Mn	V	Ta
Wt%	Balance	0.11	9.0	1.5	0.4	0.2	0.12

Table 2
The process parameters used in this study.

Laser power (W)	1400
Feed rate (mm/s)	8
Powder feed rate (g/min)	13
Overlap rate (%)	50