MRS Advances, Vol. 2, Issue 26, 2017, pp. 1393-1398
DOI:10.1557/adv.2017.124

Chemically graded Fe–Al/steel samples fabricated by laser metal deposition

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ABSTRACT

By laser metal deposition (LMD) samples from Fe–28Al (at.%) have been built on iron and various steels. Chemically graded iron aluminium and Fe–28Al/steel samples were fabricated with intended concentration gradients by controlling the feed rates of the powders. All samples were subsequently heat treated at 700 °C for 1000 h to study possible reactions between Fe–28Al and the steels and the long-term stability of the composition gradients. Microstructures were characterized by scanning electron microscopy (SEM) and concentration profiles along the building direction were analysed by energy- and wavelength-dispersive spectrometry (EDS, WDS).

INTRODUCTION

Because iron aluminides, i.e. materials based on the phases Fe_3Al or FeAl, are iron based materials, it is of interest to evaluate the possibility of fabricating chemically graded iron aluminide (Fe–Al)/steel samples. These samples will have a high wear and excellent corrosion resistance in the Fe–Al part while the steel part may be more ductile and joining to a steel structure may be easier. E.g., a turbine blade could have a steel composition at its root where it is joined to a steel disc, while the blade is fabricated from iron aluminide for high erosion and corrosion resistance.

With the advent of various additive manufacturing (AM) technologies, production of near net-shape parts from powders can be easily realised. Among these are a couple of techniques which also allow to build up chemically graded structures. These techniques are all based on powder or wire feeding. Graded Fe/iron aluminide samples have been produced by uniaxial pressing of powder stacks [1], (3D) laser cladding [2, 3] or wire-arc additive manufacturing (WAAM) [4]. In all cases binary samples with composition gradients from 0 at.% Al to over 40 at.% Al or more were obtained. The only investigation, where graded Fe–Al/steel samples have been produced by AM has been performed by laser engineered net shaping (LENS) [5]. Chemically graded thin wall tubes were successfully produced with a continuous composition gradient between Fe–28Al–5Cr–0.8Zr–0.04B and steel 1.4404 (316L). No formation of additional phases like carbides, borides or other intermetallic phases were observed and defect free samples were obtained after optimising the process parameters [5].

In this study powder based laser metal deposition (LMD) was used to produce graded samples, which is the same process as laser cladding or LENS. The aim of the present investigation is threefold: Evaluation (I) whether Fe–Al samples can be built up on different steel substrates, (II) whether chemically graded Fe–Al samples and Fe–Al/steel samples with defined composition profiles can be produced and (III) how microstructure and composition evolve during prolonged annealing.

EXPERIMENT

Gas-atomised powders of Fe–28.3 at.% Al and steel 1.4404 (316L) and of an elemental Al powder with the grain fraction 45–90 µm were used for LMD. Samples were built on different steel plates (Table 1) of 5 mm thickness either at room temperature (RT) or by preheating the substrate up to 350 °C. The surfaces of the steel plates were sand blasted for a better absorption of the laser and carefully cleaned with ethanol. The LMD experiments were performed with a 2 kW diode laser source at a Varilas 3-axis NC machine (Schuler Held Lasertechnik). Samples were built with a laser power of 200 W and a beam diameter of 0.6 mm at a scanning speed of 800 mm/min with 355 µm track distance and 400 µm layer thickness. The powder was fed by two disc powder feeders GTV PF 2/2 (GTV Verschleißschutz), using argon as carrier gas (for more details on LMD see [6]).

Microstructures of the samples were investigated by light optical and scanning electron microscopy (SEM; JEOL JSM 6490). Compositions were analysed by energy-dispersive X-ray spectroscopy (EDS) and by wave-length dispersive spectroscopy (WDS) on an electron probe micro-analyser (JEOL JXA-8100). Sections for microstructural investigation were cut by electrical discharge machining (EDM). For light optical inspection they were etched using hydrofluoric acid while for SEM they were ground to 1000 grit.

Table 1. Compositions (in at.%) of the employed steel substrates.

Elements (at.%)	C ≤ %	Si ≤ %	Mn ≤ %	P ≤ %	S ≤ %	Cr %	Ni %	Mo %	W %	V %	N ≤ %
1.4404 (316L)	0.15	1.5	2.0	0.08	0.05	17.0-19.0	9.3-13.1				0.4
1.4301 (V2A)	0.3	2.0	2.0	0.08	0.03	18.0-20.5	7.5-10.0	1.1-1.7			0.4
1.1730 (C45U)	2.3	1.5	0.4	0.06	0.06						
1.4901 (P92)	0.6	1.0	0.6	0.04	0.02	9.0-10.2	< 0.4	0.2-0.35	0.5-0.6	0.15-0.3	0.3

RESULTS AND DISCUSSION

Fe–Al samples built on different steel substrates

To evaluate the feasibility to build Fe–Al samples by LMD on different substrates, pure Fe, cast Fe–Al and the steels 1.4301 (V2A), 1.1730 (C45U) and 1.4901 (P92) were employed. Dense samples could be built on all substrates and two examples are shown in Fig. 1. All samples are defect free except for some porosity, which presumably stems from inadequate drying of the Fe–28Al powder. Also cracks developed at the sharp corners between substrate and the samples but the alloys itself show no cracks and good bonding to the substrate. EDS and WDS line scans revealed that elements from the steels introduced into the Fe–Al samples by mixing and diffusion during LMD can be traced up to about 300 µm into the iron aluminide. After annealing at 700 °C for 1000 h the bonding between the steels and Fe–Al is still perfect (Figure 2). No reaction zone with new phases or Kirkendall porosity developed between the different substrates and the iron aluminide and the initially sharp concentration jump in Al has levelled out. After annealing also the distribution of the elements originating from the steel has been determined by EDS and WDS. For the Fe-28Al/P92 sample Ni, Mo and W are detected up

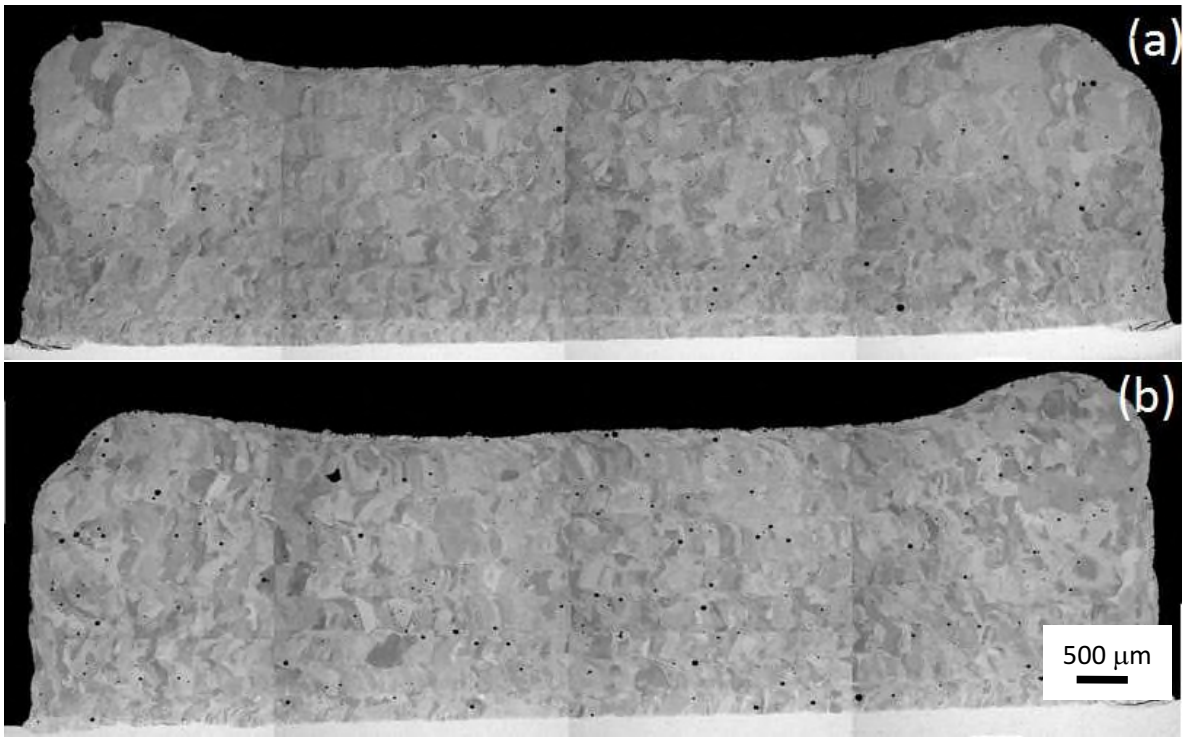

Figure 1. Back scattered electrons (BSE) micrographs of Fe–28Al built on (a) 1.4901 (P92) and (b) 1.1730 (C45U) steel substrates by LMD.

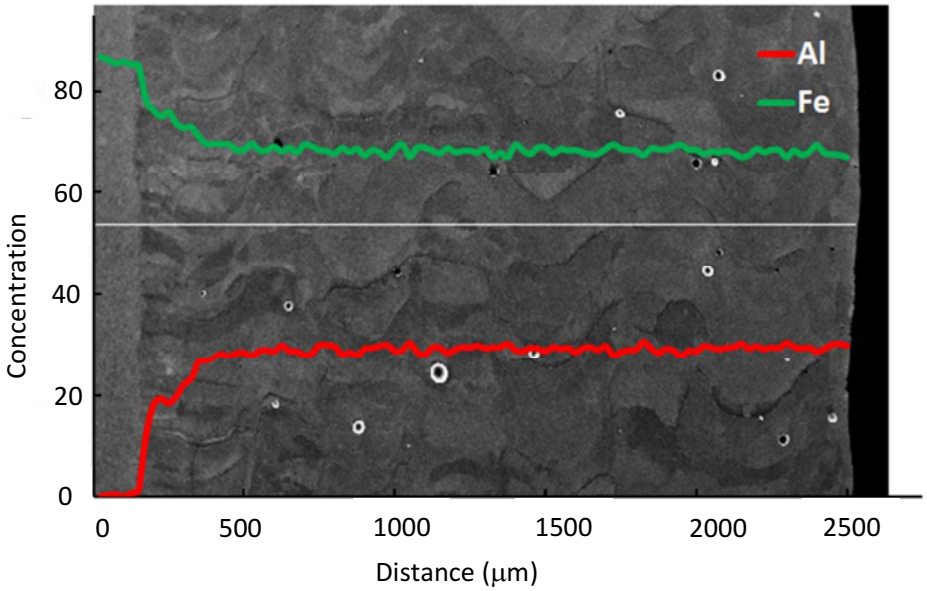

Figure 2. Secondary electron (SE) micrograph of the Fe–28Al/steel 1.4901 (P92) sample after annealing 700 °C for 1000 h. WDS line scans showing the Fe and Al concentrations are superimposed.

to a distance 200 µm within the iron aluminide. Due to its high concentration in P92 (10.2 at.%), Cr can be traced for about 600 µm into Fe–28Al. Likewise, Si is also found up to a distance of about 600 µm from the original Fe–28Al/P92 interface after annealing at 700 °C for 1000 h.

Graded Fe–Al samples with defined concentration profiles

At first, binary Fe–Al samples were produced by employing the Fe–28Al powder and the Al powder. In order to find out whether samples can be produced with defined concentrations, five different samples with constant feed rate of the Fe–28Al powder but each with another feed rate for the Al powder were produced (Figure 3). In this way samples with constant Al contents between 28 and 38.5 at.% Al were manufactured. The results show, that a linear dependence between rotation speed of the feeder and the obtained concentration exists (Figure 3). This means, that by controlling the rotation speed of the feeder, samples with defined concentration profiles can be built.

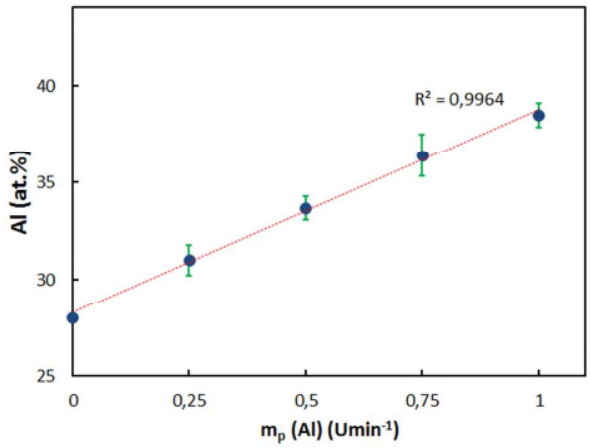

Figure 3. Dependence between rotation speed of the feeder and obtained chemical composition.

While graded samples with Al contents up to about 40 at.% Al could be built defect free, samples with higher Al contents showed severe cracking after cooling. Graded samples with Al contents up to 65 at.% Al were built at room temperature and by heating the substrate up to 350 °C. However, even the preheating did not prevent that severe cracking occurred in the samples during cooling (Figure 4). These cracks originate in the Al-rich part at the top of the sample. EPMA revealed that the upper 300 µm of the sample shown in Fig. 4, i.e. the Al rich part, consists of a two phase mixture FeAl + $FeAl_2$, followed by Al-rich FeAl below. Because the brittle-to-ductile transition temperature (BDTT) in Fe–Al increases from 200 °C below 42 at.% Al to 750 °C at about 45 at.% Al [7], even preheating at 350 °C does not prevent cracking.

Graded Fe–Al/steel samples

Graded Fe–Al/steel samples were built from Fe–28Al and 1.4404 (316L) powders. Again it was first established, that a linear dependence between rotation speed of the feeder and the concentration in the built samples exists. Following that, a number of samples with varying concentration profiles were built by either varying the feed rate of the 316L powder or of the Fe–28Al powder. Figure 5 shows a sample which covers the whole composition range between

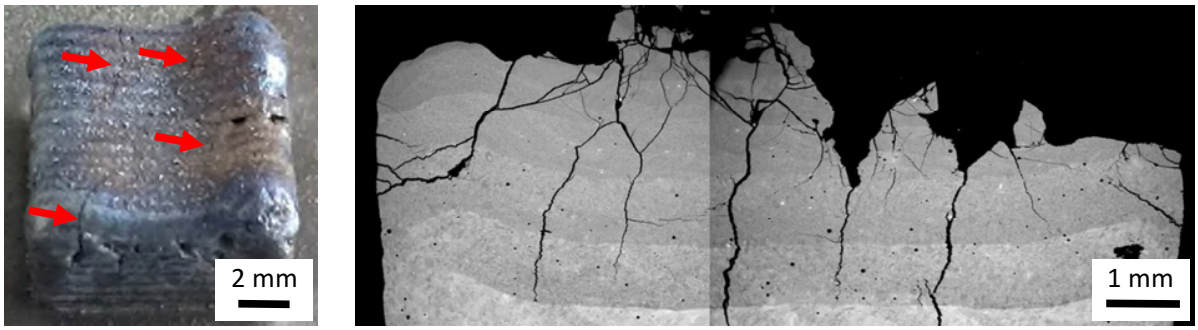

Figure 4. Graded Fe–32Al/Fe–65Al sample built by heating the substrate at 350 °C. (a) Sample after cooling showing numerous cracks (marked by arrows). (b) BSE micrograph of the cross section after cutting. The visible layering is due to different grain orientations in the deposited layers rather than corresponding to differences in composition.

Fe–28Al and the steel and which was obtained by successively increasing the feed rate of the Fe–28Al powder. While the Fe–28Al and the steel layers are defect free, large horizontal cracks are found in all intermediate layers. Possibly the cracks developed during rapid cooling of the sample, as no heating of the substrate was employed. It is assumed, that defect free samples can be built by optimising the process parameters, as it has been shown for graded Fe–28Al–5Cr–0.8Zr–0.04B/1.4404 (316L) samples produced by LENS [5]. In that case, the cracks were attributed to internal stresses which could be avoided by modifying the process parameters.

The Fe–28Al/steel samples were heat treated at 700 °C for 1000 h. Analysis by EDS and WDS showed that no intermediate phases formed during the heat treatment. This is due to the large solid solubility of Cr and Ni in Fe_3Al and FeAl [8, 9]. Figure 6 exemplarily shows WDS line scans of the Cr concentration in the as processed state and after annealing. In the as processed state clear steps in the concentration are visible when the rotation speed of the 316L powder feeder had been changed from layer to layer. After 700 °C/1000 h these steps are completely levelled out and a smooth concentration gradient is obtained. The concentration gradients of Ni and Al are levelled out comparably while the Fe content is nearly constant as there is only a slight difference in the Fe content of Fe–28Al and steel 316L.

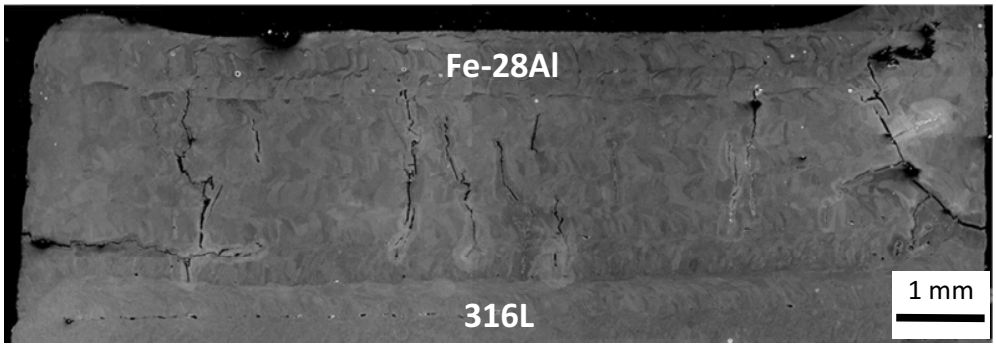

Figure 5. Secondary electron (SE) micrograph of a graded Fe–28Al/steel 1.4404 (316L) sample after annealing 700 °C for 1000 h.

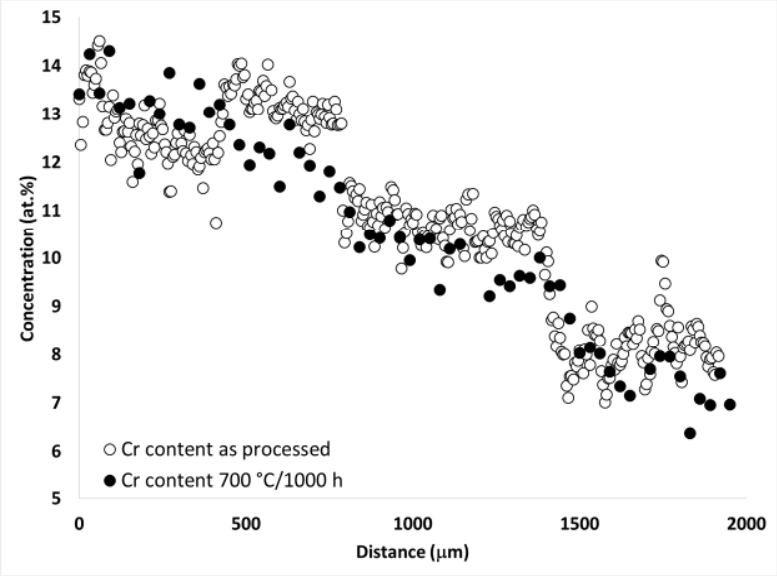

Figure 6. EPMA line scans showing the Cr content in the graded Fe–28Al/steel 1.4404 (316L) sample in Fig. 5 in the as processed state and after annealing 700 °C for 1000 h.

ACKNOWLEDGEMENT

The authors wish to thank G. Bialkowski for sample preparation by EDM and I. Wossack for performing EPMA. Partial financial support from the German Ministry of Education and Research (BMBF) under grants 03X3574E, F is gratefully acknowledged.

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